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Differences in the Exposure of the Lumbar Nerve Root Between Experts and Novices: Results From a Realistic Simulation Pilot Study With Force Sensors

Christoph Mehren, MD[1,2], Werner Korb, PhD[3,4], Esther Fenyöházi[3], Davide Iacovazzi[3], Luis Bernal, PhD[3], and Michael H. Mayer, MD[1,2]

Abstract

Study Design: Nonrandomized prospective trial.

Objective: Several studies could demonstrate "learning curves" in almost every single surgical procedure for unexperienced surgeons. This is in sharp contrast to the rising quality requirements in public health care to provide surgical training at patients "expense." The aim of this study was to visualize, measure, and set a baseline of the pressure load on the spinal nerve root during a simulated microdiscectomy on a standardized and validated model (RealSpine) under the influence of the level of surgical experience and individual skills.

Methods: Five highly experienced spine surgeons and 5 trainees without considerable surgical experience were selected to perform a standardized microsurgical discectomy on a validated RealSpine simulator. Force-torque sensors were integrated in this simulator to measure the load on the nerve root. The forces were recorded every 125 ms.

Results: We could identify cumulative for the total intervention as well as for defined single surgical steps of this procedure and as well in between the single subjects a significant higher tension and contusion forces on the nerve for the trainee group (Δp contusion 83-765 Nċs and Δp tension 159-1131 Nċs for the trainees. Δp contusion 16-171 Nċs and Δp tension 27-146 Nċs for the experts).

Conclusion: We could measure a difference between unexperienced and experienced surgeons regarding the manipulations of the nerve root during a standardized simulated microdiscectomy. This possibility could be the starting point for a new and innovative surgical education to improve outcome without negative side effects of "learning curves."

Keywords

RealSpine, surgical skills, learning curve, surgical training, nerve root manipulation, discectomy

Introduction

The education of young surgeons is part of the daily working process in hospitals. Their own experiences, as well as several studies in different surgical fields provided evidence of learning curves for surgical interventions.[1-4] It was shown that lack of experience with specific steps in an operation has a negative effect on the duration of the operation, the clinical outcome for the individual patient, as well as on the occurrence of intra- and postoperative complications.[5-8] This phenomenon is working against the constantly increasing demand for quality in the health care sector. At the same time, the cost of training and the expectations with regard to the quality of education of young surgeons are increasing.

[1] Schön Klinik München Harlaching, Spine Center, Munich, Germany
[2] Academic Teaching Hospital and Spine Research Institute, Paracelsus Medical University, Salzburg, Austria
[3] Innovative Surgical Training Technologies (ISTT), University of Applied Sciences (HTWK), Leipzig, Germany
[4] Vocationeers Salzburg, Hallein, Austria

Corresponding Author:
Christoph Mehren, Schön Clinic Munich Harlaching, Harlachinger Straße 51, 81547 Munich, Germany.
Email: cmehren@schoen-kliniken.de

It is becoming increasingly difficult to integrate surgical education into everyday clinical practice. In addition to the knowledge of how to conduct a specific intervention with regard to the corresponding individual steps, the presence of individual skills and the training of fine motor skills, hand-eye coordination and spatial imagination—the so-called "basic skills"—are essential in surgical training and education. This is particularly applicable for the field of microsurgical spinal surgery, in which the workspaces and movement margins are naturally smaller than in open surgery.

Discectomy is one of the most commonly performed surgeries on the spine. Despite the ongoing development of the currently practiced minimally invasive surgical techniques (both microsurgical and endoscopic), tensile and compressive forces inevitably act on the nerve root during the procedure. A study by Matsui et al[9] showed that both the intensity of nerve root pressure during discectomy and the duration of surgery may have a negative impact on postoperative symptoms such as radicular pain, paresthesia or paresis, as well as the duration of healing.

Systematic investigations on the patient are difficult for ethical and technical reasons. Therefore, the development of realistic simulation environments is a possible scenario so that the forces acting on the neural structures can be made measurable and objectifiable and thus making a statement possible about the quality of the operative skills or the learning progress.

The aim of this study was to visualize and measure the pressure load on the spinal nerve root during a simulated microdiscectomy on a standardized model. The related goal was to find a correlation between operative experience, that is, the number of operations performed and invasiveness, that is, the pressure load on the spinal nerve.

Material and Method

Five medical specialists and 5 medical resident medical staff from the area of orthopedic, trauma, and neurosurgery performed a microsurgical discectomy on the surgical lumbar spine simulator (RealSpine).

All resident medical staff had assisted at a discectomy prior to the simulation but had not performed this type of surgery before. The medical specialists had many years of surgical experience, each with more than, at least, 1000 independently performed microsurgical discectomies.

The present simulator has already been scientifically validated by Adermann et al.[10] The lumbar surgical simulator is based on artificial materials with a realistic anatomy and integrated bleeding system and realistically represents a L4/L5 herniated disc. The RealSpine test environment is available for discectomy, which simulates the process of the surgical procedure on a model. The model used was created based on real patient data (magnetic resonance imaging [MRI] and computed tomography [CT] data) and modeled in 3 dimensions. On this basis, the molds were printed, from which the anatomical structures were modeled. RealSpine contains all the anatomical structures relevant to lumbar spine surgery. An electronic blood system produces artificial blood to increase the reality level of the simulation system.

The system has been used in preclinical testing and training workshops for several years now.

This simulation study was approved by the institutional review board.

Simulated Patient Case

All probands of the study were educated about the patient case via clinical data (patient file) as well as MRI. The simulated patient has had left-sided motor deficits for L5 for the past 4 weeks, as well as increasing sciatica with a projection to the dermatome L5. The clinical examination showed a peroneal paresis 2/5 left-sided as well as paresthesia. Straight-Leg-Raise-Test (SLR) is positive on the left side at 45°. The patella tendon reflexes and Achilles tendon reflexes are weakened on the left side. The MRI shows at level L4/5 a sequester left in direction to caudal with a clear compression of the nerve root.

The task of the trainees was to provide the indication for the surgical treatment and then to perform the surgery in a simulation environment in 5 steps. The surgical steps of the sequestrectomy are performed microscopically through the interlaminar approach. In order to better standardize the surgery within the study and the evaluation possibilities, the procedure was divided into 5 steps:

1. Laminotomy
2. Opening of the flavum
3. Access to the nerve root
4. Mobilization of the disc herniation
5. Removal of the disc fragment and inspection of the intervertebral disc space.

Preparation of access to the interlaminar window was not necessary. All measured values were recorded and evaluated in accordance with the predetermined surgical steps.

The simulation environment contains all the anatomical structures that are relevant for lumbar spine surgeries: ligamentum flavum, lumbar vertebrae L4 and L5, posterior longitudinal ligament, herniated disc consisting of annulus fibrosus and prolapsed nucleus pulposus, epidural fat, dura with spinal nerves and cerebrospinal fluid. In addition, a 3-point bleeding system was integrated for diffuse bleeding in the upper part of the simulator, epidural bleeding, and osseous bleeding.

The simulation system integrates also a force-torque sensor system. This allows the measurement of the strain on the spinal canal as well as on the nerve root during the simulated surgery for analyzing the strain objectively. The measuring principle is based on a length-time difference measurement of sonic pulses. The nerve structures are simulated with silicone tubes. The embedded ultrasound system is analyzing the contusion as well as the tension with the pulse-echo method. Therefore, short sonic signals are sent and the resulting transmissions as well as the reflections ("echoes") are evaluated—similar to clinical echography. The evaluation is performed during the simulation with a 2-capsula architecture. A sonic transmitter is mounted on the simulated nerve root at one end of the tube, a sonic receiver is mounted on the other end as illustrated in Figure 1. The transmission path is the silicone tube. The technical analysis included pulse width, absorption as well as time shift of the transmitted signal—this allows conclusions about deviations of cross-section and length of the tube as demonstrated in Figure 2. This allows the analysis of nerve contusion (measurement of absorption) and nerve tension (measurement of the time shift).

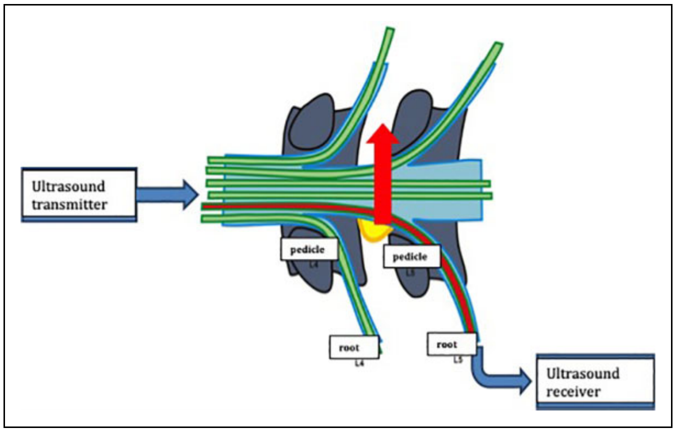

Figure 1. Measurement principle for the analysis of nerve root contusion and tension.

The sampling rate for the measurements is 125 ms. The acquired signals were converted into newton, which are selected from a calibration matrix. The calibration matrix was established in a calibration measurement experiment. Therefore, a 3D rotation platform was mounted on a 3D coordinate table. The calibration was performed in 6 degrees of freedom (DOF) with a 6-DOF force-torque sensor (ME-Messsysteme, Hennigsdorf, Germany). Each value of this 6-DOF-force-torque sensor was stored together with the corresponding echo signal.

During the surgery with the simulator every echo signal is transferred via wi-fi together with a time stamp to an external computer.

The assessment of the simulated procedures included time and force distribution. The recorded videos supported the assessors improving their understanding in the analysis.

The assessment is classified into novices versus experts as well as into steps 1 to 5. The location and scattering parameters of the data were analyzed with a descriptive analysis. The main emphases are given to the arithmetic mean, median,

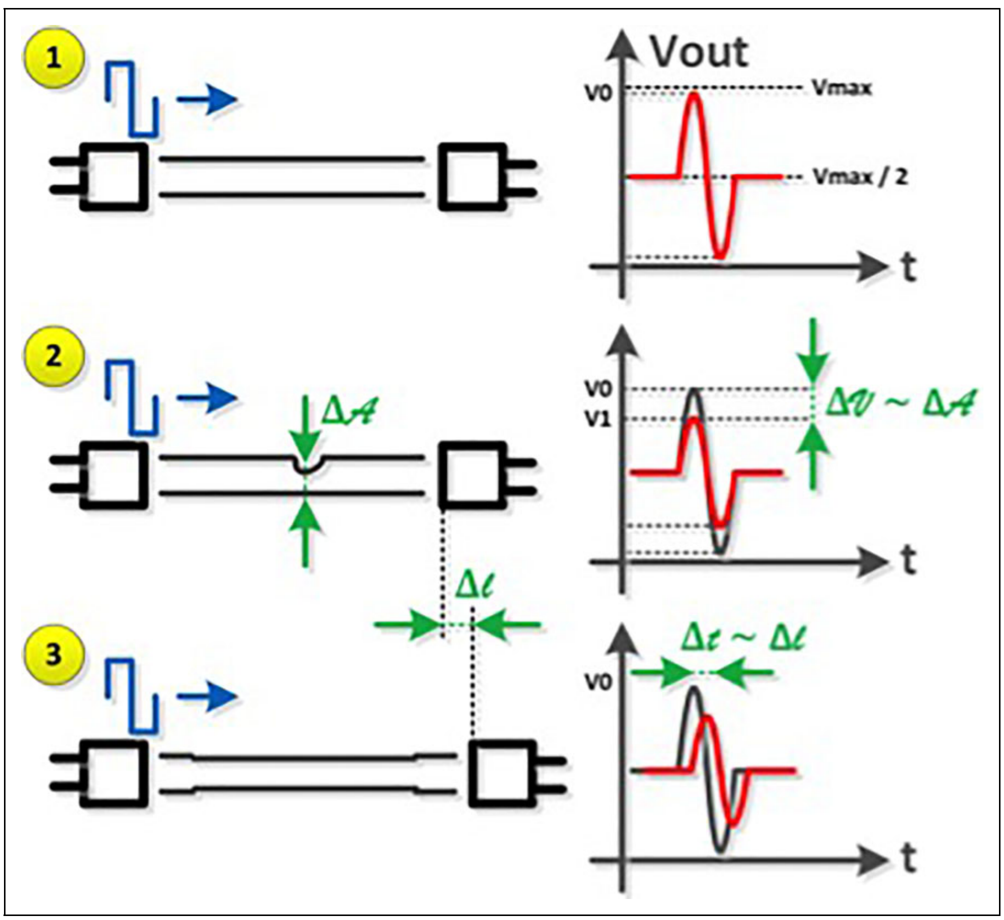

Figure 2. The signal in (1) is the normal signal of a non-touched nerve root. In (2) the analysis of the nerve contusion (measurement of absorption) and in (3) the nerve tension (measurement of the time shift) is shown.

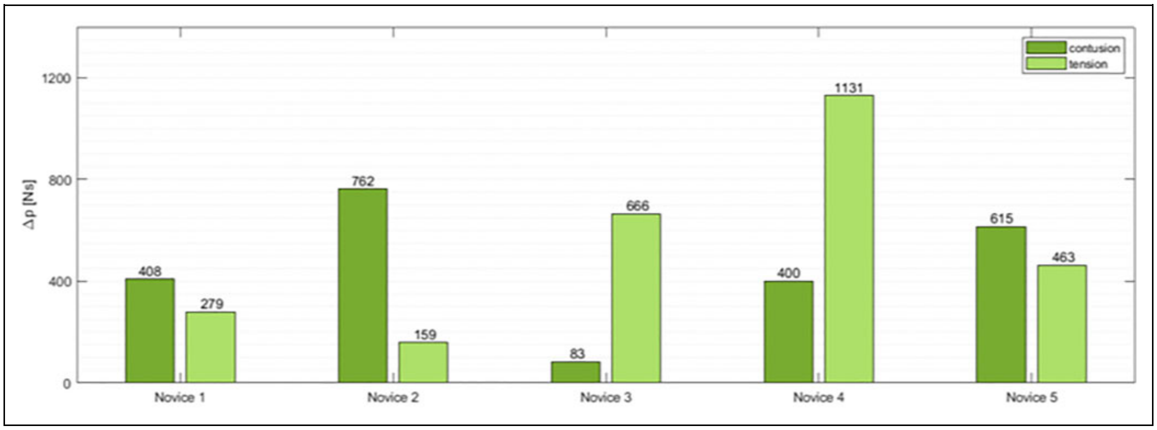

Figure 3. Summation of applied impulses by every novice in newton seconds (Nċs) for the whole operation.

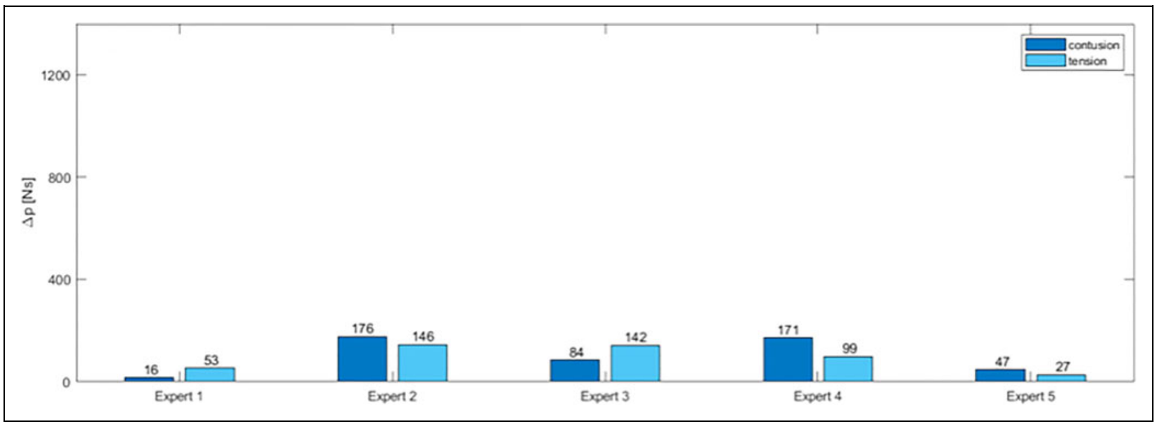

Figure 4. Summation of applied impulses by every expert in newton seconds (Nċs) for the whole operation.

and the minima and maxima of the forces during the measurement time period. Therefore, the variance and standard deviation were determined. The impulse was computed, that is, the integral of the force over time, leading to an improved comparability

$$\vec{F}\,.\,\Delta t = m\,.\,\Delta\vec{v} \quad \text{or} \quad \vec{I} = \Delta\vec{p}$$

This allows the determination of the force affecting the body over time.

The surgical technique and the speed of surgery of each consultant could be selected individually in accordance with their own usual procedure. Nevertheless, the aforementioned 5 surgical steps had to be strictly respected. All 5 steps were recorded on video (via surgical microscope) separately per participant, the time, the surgical steps and force data also being recorded.

An experienced surgeon assisted the five novices. In these simulation procedures as well, participants were able to select surgical technique and speed but were required to follow the five surgical steps in order to keep the study standardized. The experienced surgeons (study leaders: CM and MM) supervised the correct execution of the predetermined 5 surgical steps without giving instructions or tips.

Results

For the evaluation, the data of experts and novices was compared and evaluated against each other.

The average medical experience of the novices (resident medical staff) was 3.2 years (1.5-4 years), the experts (consultants) having an average experience of 15.4 years (8-25 years). The average operation time of novices was 36.5 minutes and the average operation time of the experts was 14.2 minutes.

The group of novices applied cumulatively higher contusion and tension forces to nerve root L5 than the experts. Also, the forces and the duration of the internally applied forces of the novices and the experts had a high variance.

The novices differed strongly not only in the characteristic expression with each other (Δp-contusion: 83-765 Nċs | Δp-tension: 159-1131 Nċs) but also the respective relationship between contusion and tension had large spans as demonstrated in Figure 3. On the other hand, the characteristics of the experts are more or less on a similar level (Δp-contusion: 16-171 Nċs | Δp-tension: 27-146 Nċs), as well as the ratio of the span between contusion and tension is less as shown in Figure 4.

Also within the a priori defined surgical steps ((1) laminotomy, (2) opening of the flavum, (3) access to the nerve root, (4)

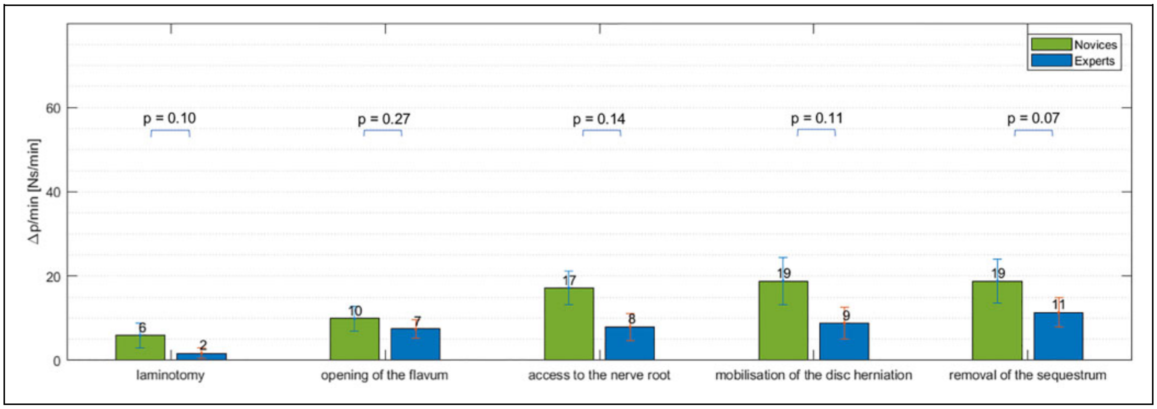

Figure 5. Mean values of impulse for contusion in newton seconds per minute (Nċs/min) for every step, comparing novices and experts.

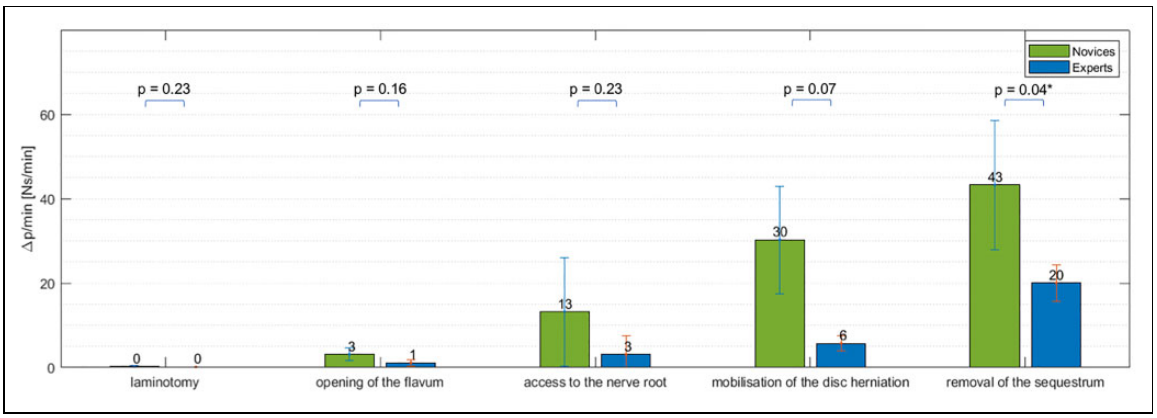

Figure 6. Mean values of impulse for tension in newton seconds per minute (Nċs/min) for every step, comparing novices and experts.

mobilization of the disc herniation, (5) removal of the sequester), a significant difference of the applied impulse per minute between the groups was identified. As demonstrated in Figures 5 and 6, the average applied impulse per minute (mean) differ for each surgical step. An increase of the contusion and tension of the nerve root during the intraspinal preparation (steps 3-5) was identified. The values of the novice-applied impulses are nearly twice the values for the experts. During step 4, the novices applied, on average, 5 times higher tension forces than the experts (30 vs 6 Nċs/min).

Figures 7 and illustrate the average values of the applied impulses in newton for each surgical step and distinguish novices and experts as well as distinguishing contusion (Figure 7) and tension (Figure 8). The bar's trends are similar, just the experts have applied considerably lower impulses compared with the novices (novices about the factor 4 higher than the experts for contusion and a factor 10 higher for the tension, particularly in steps 2 to 4).

For the maximum applied impulses, there are no differences between novices and experts. For the contusions at the mobilization of the disc herniation (step 4), the experts had even higher values than the novices (Figure 9) (6.4 vs 2.2 N). There is no obvious difference for the tension for both groups (Figure 10).

Discussion:

Studies by Matsui et al[9] have shown that intraoperative pressure loads on the nerve root can cause negative effects such as local inflammatory reactions, damage to the nerve root, and postoperative radicular pain and, moreover, it can have a major impact on the healing period. Although compressive stress on the spinal nerves and surrounding structures cannot be avoided in a discectomy, the intraoperative manipulation of the neural structures should be kept to the lowest level possible. This represents the great challenge between the unavoidable learning curve during the time of further education of young residents and the increasing quality demands of the health care sector.

So far, there are only a few studies[11-13] on mechanical stress on the nerve root, since from an ethical point of view, such measurements on living patients are hardly feasible. Alternatively, human specimens or (living) animal models may be considered for measurements of stress on the spinal nerve root due to their proximity to reality. Disadvantages, however, are high costs, ethical concerns, the largely missing pathology (herniated disc) and the altered tissue properties after fixation of the specimens. As a result, meaningful measurements are feasible to only a limited extent.[10] More suitable models are virtual reality (VR) simulators or surgical simulation systems

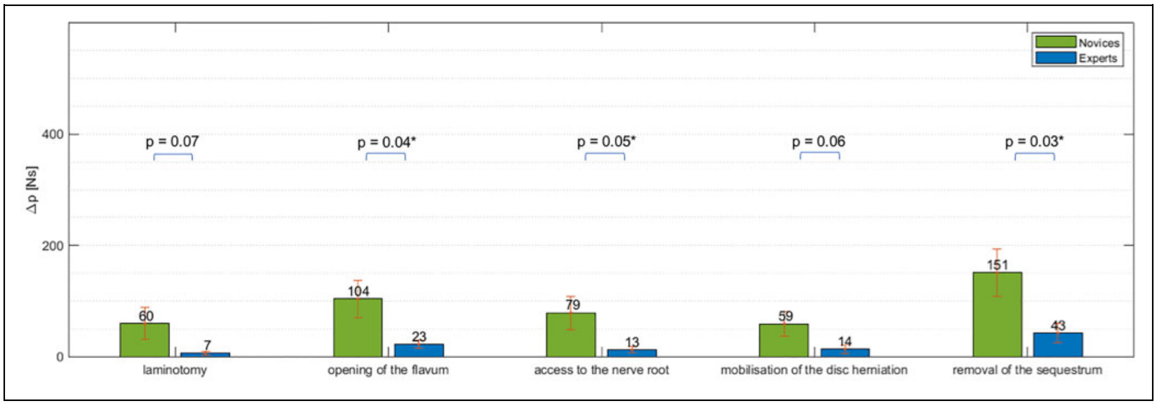

Figure 7. Mean values of impulse for contusion in newton seconds (Nċs) for every step, comparing novices and experts.

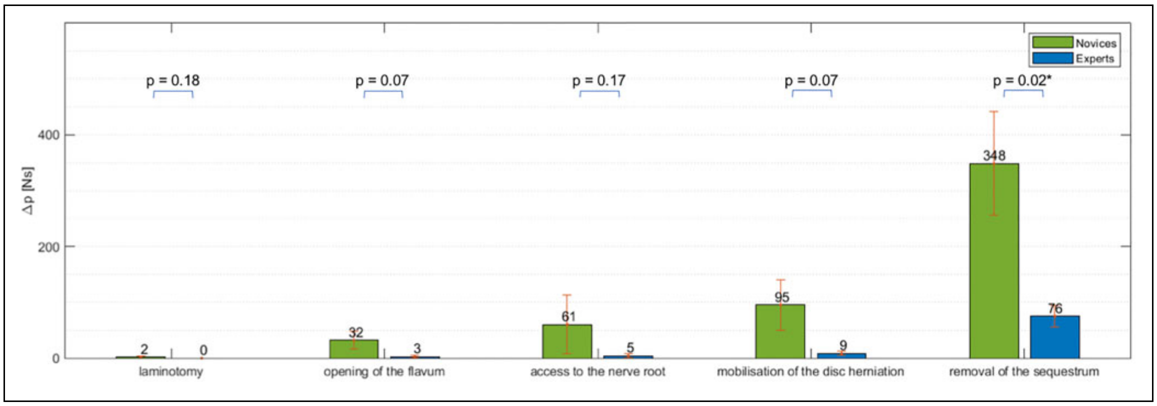

Figure 8. Mean values of impulse for tension in newton seconds (Nċs) for every step, comparing novices and experts.

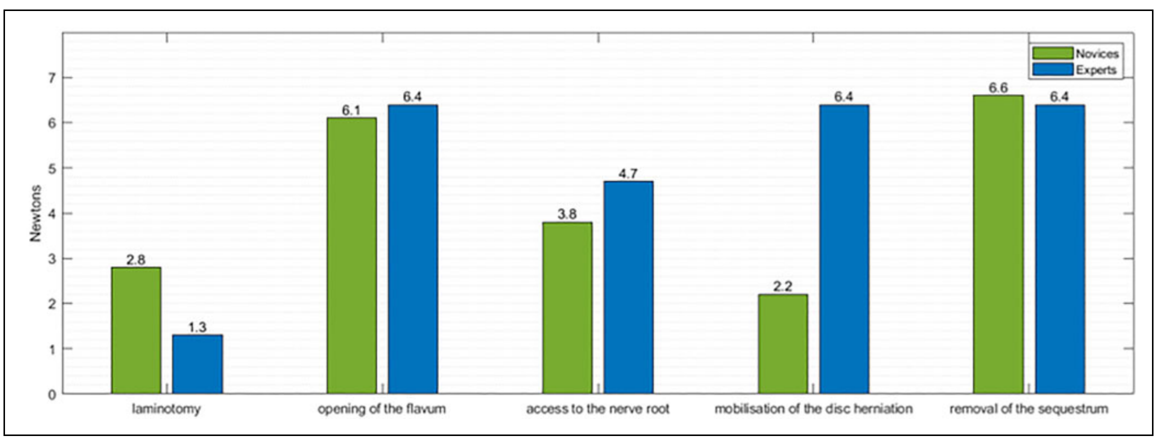

Figure 9. Maximum of contusion force applied by novices and experts for every step.

consisting of synthetic material with realistic anatomy, as they have different pathologies and can simulate different degrees of complications such as dural tear with cerebrospinal fluid leakage or bleeding. The disadvantage of VR simulators is the lack of realistic haptic, which is very well provided for in synthetic surgical simulators.

In some studies, the realism and very good haptic properties of the surgical simulation system used in the present study have already been proven.[10] In addition, such models can be used to create a standardized test environment in which measurements can be repeated as often as desired under the same conditions in order to objectively document learning progress.

The results of the present study show that experts and novices sometimes have similar contusion and tension force values, but the experts have a much shorter interval and a shorter duration of surgery. It can therefore be assumed that as the surgeon's experience increases the duration of the

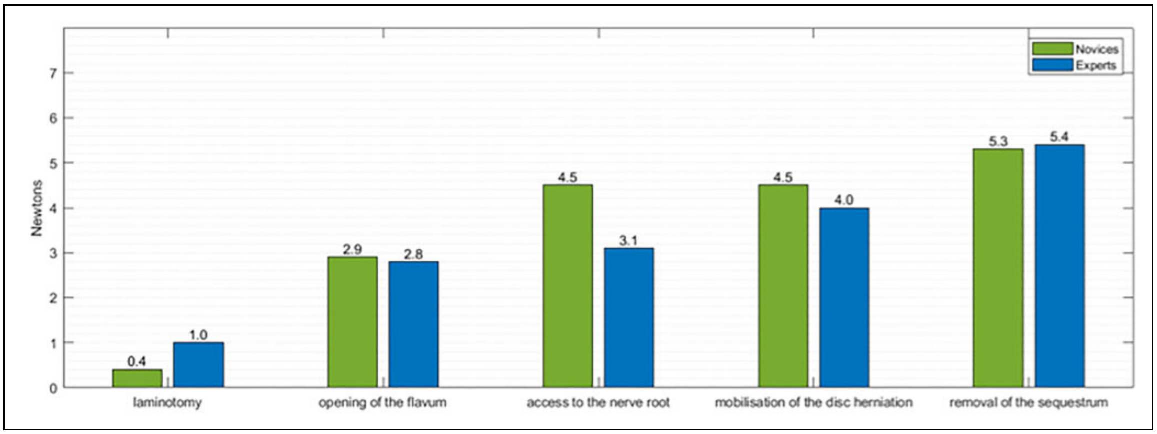

Figure 10. Maximum of tension force applied by novices and experts for every step.

operation can be shortened and thus the intraoperative stress on the nerve root and the resulting damage can be reduced.

In the context of this pilot study, a significant difference between experienced and unexperienced surgeons with regard to nerve root manipulation in a standardized discectomy could be measured. This result corresponds to the expectations when we compare our findings to other studies on the learning curves and existing technical skills for surgical procedures.[3-8,14] In addition, a high construct validity for the simulation system used in the study can be demonstrated if we apply the usual definitions for validity of simulators.[15]

The total pressure load on the nerve root in the present model is also closely related to the time-required interval. This in turn is closely related to manual "basic skills" such as hand-eye coordination, fine motor skills or 3D visualization. Manual basic skills could alternatively be trained by means of serious games. In recent years, the development of the educational game industry has progressed so far that serious games can be used as much as VR simulators for the training of basic surgical skills. In addition, learning games possess a dimension of entertainment.[16] The study by Boyle et al[17] analyzed the effect of video games on the surgical skills of novices. It has been shown that all subjects had an increase in performance compared with the control group when performing laparoscopic tasks after playing video games regularly, both in terms of speed and accuracy of execution.

Also, Schlickum et al[18] could give evidence of a positive effect of video games on surgical skills. As a result, regular training with realistic simulators, VR simulators, and serious games can improve surgeons' surgical skills and reduce the duration of surgery.

The study by Bjerrum et al[19] shows a similar result. A comparison between novices and experts disclosed an improvement of surgical skills during an appendectomy on the virtual simulator in the period examined (20 repetitions on the surgical simulator). Time, distance, and other surgery-specific parameters were compared. Furthermore, they suggest using virtual simulators as an assessment tool. Key advantages in the use of simulation systems for the measurement and evaluation of the surgical performance are, according to the study, the automated and standardized test conditions and measurement parameters. These are also given in the simulation system—RealSpine—used in the present study. Nevertheless, further validation studies with further measurement results must be carried out before the simulator can be used as an assessment tool. In addition, further surgery-specific parameters need to be used for an assessment, as an assessment based solely on time and distance is inadequate.

In the present study, the small sample size and the lack of baseline at which damage to the nerve root could be expected could limit the representativeness of the present study. Nevertheless, the constancy of the values of the 5 experts makes it possible to establish this median value as a benchmark to achieve for every "beginner" of this surgical intervention. Further studies are necessary and planned in order to be able to demonstrate learning success by novices through simulation training and also to draw conclusions on the surgical talent of young surgeons on the basis of the contusion and tension forces.

Conclusion

In recent years, the demand for simulation training in medicine has increased enormously. In particular, virtual reality simulators are increasingly used for the training of special skills in various fields of medicine such as orthopedics.[20] This facilitates the training for real surgical situations and complications can be trained for as often as desired and without risk for the patient. The presented study may provide a starting point for the development of an innovative surgical training approach to microsurgical intraspinal spine surgery, while simultaneously minimizing negative learning curve effects in favor of a positive outcome for the patient.

Overall, realistic surgical simulation systems offer tremendous potential for further studies under consistent conditions and with different pathologies without risk to the patient.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Werner Korb was and Luis Bernal is CEO and shareholder of Realists Training Technologies GmbH Leipzig Germany, owner of the trademark "RealSpine." The other authors certify that they have no commercial associations that might pose a conflict of interest in connection with the submitted article.

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ORCID iD

Christoph Mehren, MD https://orcid.org/0000-0001-9681-6028

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