



## Surgeon's comfort: The ergonomics of a robotic exoscope using a head-mounted display



Anto Abramovic<sup>a,1</sup>, Matthias Demetz<sup>a,1</sup>, Aleksandrs Krigers<sup>a</sup>, Marlies Bauer<sup>a</sup>, Sara Lener<sup>a</sup>, Daniel Pinggera<sup>a</sup>, Johannes Kerschbaumer<sup>a</sup>, Sebastian Hartmann<sup>a</sup>, Helga Fritsch<sup>b</sup>, Claudius Thomé<sup>a</sup>, Christian F. Freyschlag<sup>a,\*</sup>

<sup>a</sup> Department of Neurosurgery, Medical University of Innsbruck, Anichstr. 35, 6020, Innsbruck, Austria

<sup>b</sup> Division of Clinical and Functional Anatomy, Medical University of Innsbruck, Müllerstr. 59, 6020, Innsbruck, Austria

### ARTICLE INFO

#### Keywords:

Neurosurgery  
Robotics  
Exoscope  
Surgeons' ergonomics  
Microsurgery  
Microscope

### ABSTRACT

**Introduction:** Conventional microscopes have certain limitations in terms of posture and ergonomics. Monitor-based exoscopes could solve this problem and thereby lead to less work-related sick leave for surgeons.

**Research question:** The aim of this study was to assess the ergonomics, usability, and neurosurgeon's comfort of a novel three-dimensional head-mounted display-based exoscope in a standardized setting.

**Material & Methods:** 34 neurosurgeons participated in a workshop on the exoscope, which features a head-mounted display and a head gesture-triggered control panel. After completion of a custom-made 10-step microsurgical exercise, image quality and comfort were assessed using a questionnaire. The participants' posture during the exercise was analyzed using a video motion analysis software.

**Results:** 34 participants (median neurosurgical experience: 6 years) were included. The median time to complete the exercise was 12 min [IqR 9.4, 15.0]. Younger participants ( $p = 0.005$ ) and those with video game experience ( $p = 0.03$ ) had a significantly steeper learning curve. The median overall satisfaction was at 80% in general and 82% for image quality. The median upper body as well as the median head coronal displacement from the neutral axis were 0°. Participants with less microsurgical experience showed less head/body displacement during the exercise ( $p = 0.01$ ).

**Discussion and conclusion:** Using the microsurgical training tool, we were able to depict a steep learning curve with a sufficient learnability of the most relevant commands. The exoscope excelled in usability, image quality as well as in ergonomic and favorable posture and could thus become an alternative to conventional microscopes due to the potentially elevated surgeons' comfort.

### 1. Introduction

Since the first use of the microscope for a neurosurgical procedure, surgeons and industry were striving to evolve this tool towards being the essential piece of neurosurgical equipment to date (Uluç et al., 2009). Despite tremendous technical advances, modern microscopes still comprise disadvantages, such as limited mobility and angulation, the need to operate the microscope through switches (footswitch, mouthpiece, handlebar) but additionally physical discomfort experienced by neurosurgeons due to potentially unergonomic postures (Figueiredo et al., 2020; Weinstock et al., 2021; Helayel et al., 2021). The discomfort during surgical interventions and its impact on the long-term working

ability has gained importance in the past decades, especially due to the increment of surgical complexity and duration (Siller et al., 2020). Previous studies have already demonstrated an increased risk of work-related musculoskeletal disorders (WMSDs) and degenerative spinal deformities for surgeons performing microsurgical procedures (Lavé et al., 2020; Auerbach et al., 2011). Especially spine surgeons are at risk of WMSDs by working for hours in non-neutral positions, with flexion of the neck and coronal malalignment as they perform microscopic surgeries in a standing position, frequently leaning over the operating field (Park et al., 2012). Improving these shortcomings may lead to a reduced number of days absent due to sick leave and a higher long-term working ability for surgeons (Oertel and Burkhardt, 2017; Roethe et al., 2020; Mamelak et al., 2010).

\* Corresponding author. Department of Neurosurgery Medical University of Innsbruck, Anichstraße 35, A-6020, Innsbruck, Austria.

E-mail address: [christian.freyschlag@i-med.ac.at](mailto:christian.freyschlag@i-med.ac.at) (C.F. Freyschlag).

<sup>1</sup> denotes Co-First Authorship.

<https://doi.org/10.1016/j.bas.2021.100855>

Received 28 October 2021; Received in revised form 13 December 2021; Accepted 16 December 2021

Available online 28 December 2021

2772-5294/© 2021 The Authors. Published by Elsevier B.V. on behalf of EUROSPINE, the Spine Society of Europe, EANS, the European Association of Neurosurgical

Societies. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

### Abbreviations

WMSDs	work-related musculoskeletal disorders
RS	RoboticScope
HMD	head-mounted display
EVA	Ethylene vinyl acetate

In recent years, exoscopes have gathered advantages compared to the conventional surgical microscope. Not only a more comfortable posture for the surgeon, but also the technical prospects of fully digitalized image processing and robot movement have been included. In contrast to previous microscopes, exoscopes do not project the image into fixed eyepieces, but onto external mobile screens (Amoo et al., 2021). Nevertheless, due to the distance between the surgeon and the monitor, exoscopes still harbor limitations regarding the depth of the visual field and the visual quality at higher magnification (Ricciardi et al., 2019; Herlan et al., 2019; Gonen et al., 2017).

The RoboticScope (RS; BHS Technologies GmbH, Innsbruck, Austria) was designed to overcome this issue by projecting the images on external displays directly in front of the eyes, comparable to virtual reality (VR) goggles. The RS consists of a head unit containing 2 video cameras mounted onto a 6-axes robotic arm. The image is displayed to the surgeon via two digital micro-displays (Head-mounted display, HMD) that provide a three-dimensional image of the surgical field in real time (Fig. 1). Another major advantage is the hands-free control of the robotic arm that has been implemented and uses head gestures on a virtual interface (Fig. 1). A foot pedal serves as a safety measure against uncontrolled movements of the RS by only reacting to head gestures when the pedal is pressed. General head movements (for example to achieve a comfortable posture for the surgeon without moving the robotic arm) do not change the camera position, if the foot pedal is not pressed. The RS has already been successfully tested on cadavers and in the clinical setting, where especially hands-free control and visualization quality were reported as major advantages (Schär et al., 2021).

The aim of this study was to investigate the ergonomics, usability and neurosurgeon's comfort of the novel three-dimensional head-mounted display (HMD)-based exoscope in a standardized setting.

## 2. Material & methods

### 2.1. Inclusion of study participants

Neurosurgeons of different levels of qualification (n = 34; 15 senior consultants, 2 consultants, 12 residents, 5 interns; 21 men, 13 women) from the authors' department participated in a workshop including a demonstration of the exoscope as well as skill training using a standardized microsurgical training tool. Participants were not previously trained on the device and signed a written informed consent form for the use of their data and video footage in pseudonymous form. Prior to enrollment, each participant was assigned a study ID, which was documented on the paper- and electronic-based case report forms (CRFs) as well as the video recording screen.

### 2.2. Pre-interventional training

Stereoscopic vision was tested using a commercially available standardized stereoscopic vision assessment tool (Stereo Fly test, Stereo Optical Company Inc., Chicago, IL, USA). Each participant received a personal 30-min user instruction performed by the staff of BHS Technologies GmbH prior to conduction of the microsurgical skills assessment. The participant's interpupillary distance and visual impairments (shortsightedness, farsightedness) were compensated at the HMD by means of dioptric compensation. Following the instruction, the participants received the HMD to test the commands with technical assistance. Participants were instructed on how to use the foot pedal as well as the HMD to execute the most important commands (Step 1: press the foot pedal, Step 2: Choose the command at the user interface by pointing the cursor with head movement Step 3: Leave the foot pedal to activate the command). The execution of each training step had to be ticked in an electronic CRF to allow for a standardized pre-interventional training.

#### 2.2.1. Customized microsurgical training tool assessment

A custom-made microsurgical training tool was designed by one of the authors (AA) in order to perform a quantitative analysis of the exoscope usability. The microsurgical tool contained ten eyelets set at different angles, thereby forcing participants to use different head gesture commands with the HMD, respectively. The training tool consists of a base plate made of Ethylene vinyl acetate (EVA) and ten metal pins which were pierced through the ground plate. Prior to affixing small eyelets (inner diameter: 1 mm), the metal pins were bent using needle-nose pliers to create different angles. A paint marking of the beads as well as a number marking on the base plate served to guide the direction



**Fig. 1.** Start position of the participant with HMD set up and exercise centered on the working table (A). Operating the robot controlled exoscope with the user interface (B, 1 = orbit movement, 2 = magnification, 3 = translating movement, 4 = focus).

of the course.

Participants were asked to perform this exercise using microsurgical instruments (needle holder, forceps) and a 6/0 nylon suture. The standardized course of the exercise consisted of centering and aligning each eyelet using the tilting option of the RS, followed by threading the needle through the eyelet with the help of a needle holder and/or forceps. Prior to passing the needle, each eyelet had to be centered, so that the hole was no longer visible due to the perpendicular view (Fig. 2). The same steps had to be applied for each eyelet, thereby provoking various exoscope positions. The working distance as well as the starting position were standardized to provide consistent data. In case of a technical problem, such as slipping of the HMD, technical assistance by the manufacturer was present.

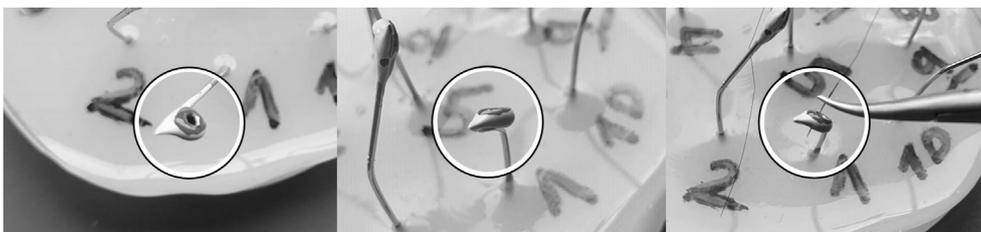
### 2.2.2. Participant questionnaire

Following the execution of the training exercise, participants were asked to fill out an electronic 28-item questionnaire including 5-point Likert scales and text answers. In addition to basic data of each participant (e.g., age, gender, right/left-handed, neurosurgical experience), the survey consisted of questions regarding previous experiences with various virtual reality (VR), video games as well as usability and comfort using the novel exoscope.

### 2.2.3. Video analysis

The video analysis system of the training exercise consisted of five cameras recording different angles of the exercise itself, as well as the participant- and exoscope movements (Fig. 3). The front side camera as well as the exoscope video recording were used to monitor the centering and angulation process of every single eyelet throughout the exercise, moreover, possible operating errors by participants were documented as well. The quantitative analysis of correctly centered eyelets was evaluated with a custom-made "Bullseye-Score" (Fig. 4). The qualitative video analysis was performed by all authors, including documentation of time required for performing the whole exercise, time per eyelet, operating errors, commands per exercise and commands per eyelet using a custom-made CRF.

One video camera was placed exactly behind the participant in order to provide accurate video footage for the quantitative 2D-video motion analysis performed by appropriate software (Kinovea, v. 0.9.3). Standardized coronal angle measurement was performed for the upper body as well as the head movement (Fig. 5). The video analysis was performed by two of the authors (MD, AA) following a standardized video analysis protocol. Operating errors were defined as commands for the RS that were either not executed due to incorrect handling (i.e. foot pedal not pressed) or were immediately corrected by the participant (i.e. wrong command chosen). Angular movements from the starting position (angle per second; °/s) were measured and documented in a Windows Excel sheet (Microsoft Office, Version 1908, Microsoft, Inc., Redmond, WA, USA). The angulation limit was defined at reaching a maximum excursion of the RS, from where repositioning or readjustment became necessary.



**Fig. 2.** Standardized microsurgical test with eyelets shown from different perspectives. Participants were asked to perform the exercise in a standardized fashion for each eyelet (Step 1: Centering of the eyelet, Step 2: Tilting the exoscope until the hole of the eyelet was not visible, Step 3: Threading the 6/0 needle through the hole).

### 2.2.4. Statistical analysis

Statistical analysis was performed using IBM SPSS (IBM SPSS Statistics, version 24.0, IBM Corporation, NY, USA). Data normal distribution was checked by histograms and Kolmogorov-Smirnov-test. Mann-Whitney-U-test, Wilcoxon rank sum test, Chi (Figueiredo et al., 2020) test or Spearman's rank correlation coefficient test were used to detect significant similarities or differences. A p-value of  $\leq 0.05$  was considered statistically significant.

### 2.3. Theory

The authors' theory was that due to the hands-free HMD the posture and ergonomics of neurosurgeons could be improved and thus the RS could become an alternative to conventional microscopes. However, it had to be determined using a standardized procedure whether the usability of this novel exoscope can be learned quickly and how the participants' satisfaction with, for example, depth of field and resolution is.

## 3. Results

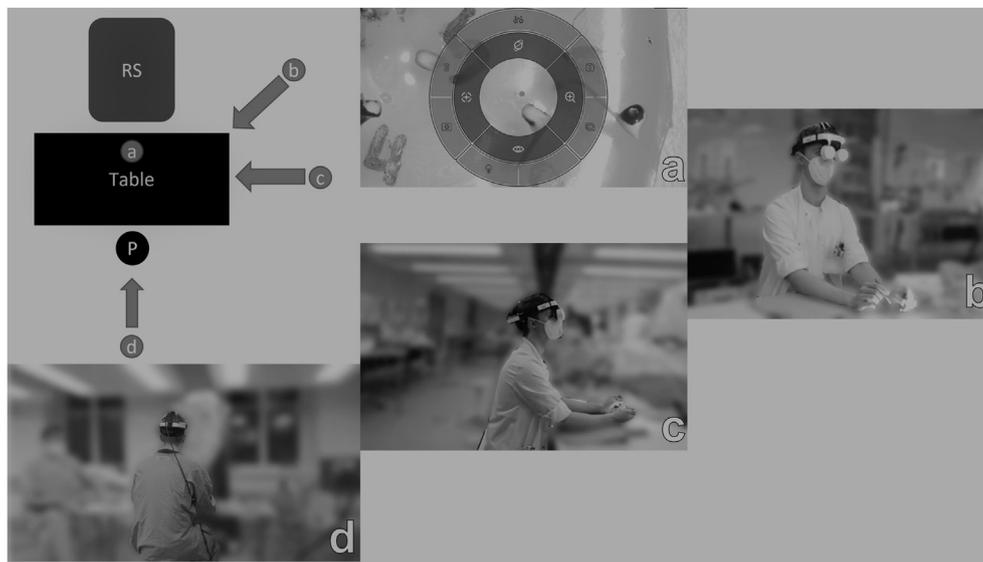
34 participants (21 men, 13 women; mean age:  $35 \pm 9$  years) were included. The median neurosurgical experience amounted to  $6 \pm 1.4$  years. 62% of the participants had experience with videogames and 9% had already used virtual reality (VR) headsets.

### 3.1. Microscopic training exercise

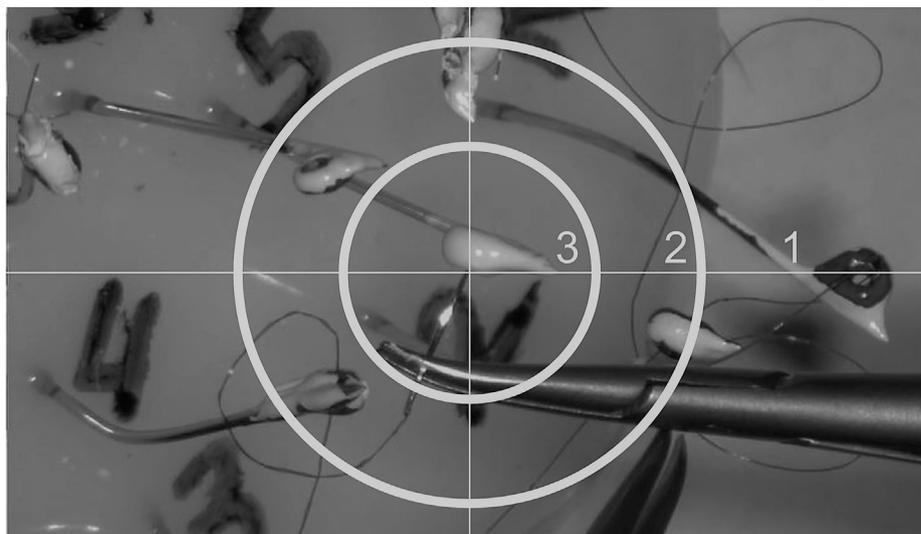
The median time needed by participants to complete the exercise was 12 min (inter-quartile range [IqR] 9.4, 15.0) with significantly less time needed for eyelet 7–10 compared to eyelet 2–5, especially in younger participants ( $p = 0.005$ ,  $r = 0.49$ ), further the participants with video game experience showed significantly less time to complete the entire exercise ( $p = 0.05$ ). The median Bulls-Eye score amounted to 27/30 (IqR 24; 28). The median number of commands to finish the entire exercise was 38.5 (IqR 28.3, 42.8). The median number of operating errors was 3.5 (IqR 1.0, 7.0). 12.5% (4/28) of the participants needed technical assistance during the conduction of the exercise. In the median, the angulation limit of the RS was reached 2 times per participant (IqR 1.0, 4.0).

### 3.2. Surgeon's questionnaire

In general, the participants had no major difficulties using the RS, the median overall satisfaction was at 80%. There was no significant difference between younger and more experienced surgeons with regard to technical difficulties except that younger participants had less difficulties with the user interface and the HMD commands of the RS ( $p = 0.014$ ). Overall satisfaction with the image quality of the RS was 82%, this correlated significantly with the preference to use the device more often during surgery ( $p = 0.001$ ) as well as feeling confident using the RS in by themselves ( $p = 0.004$ ). A majority of 88% of the participants reported to feel safe enough to use the RS in the OR with technical assistance.



**Fig. 3.** Workflow diagram showing the position of the exoscope (RS) as well as the different camera positions and the corresponding video angles (a–d).



**Fig. 4.** Bullseye score. Each eyelet was assessed respectively, thereby creating a score reaching from 10 (minimal centering of each eyelet) to 30 (optimal centering of each eyelet).

### 3.3. Quantitative 2D-video motion analysis

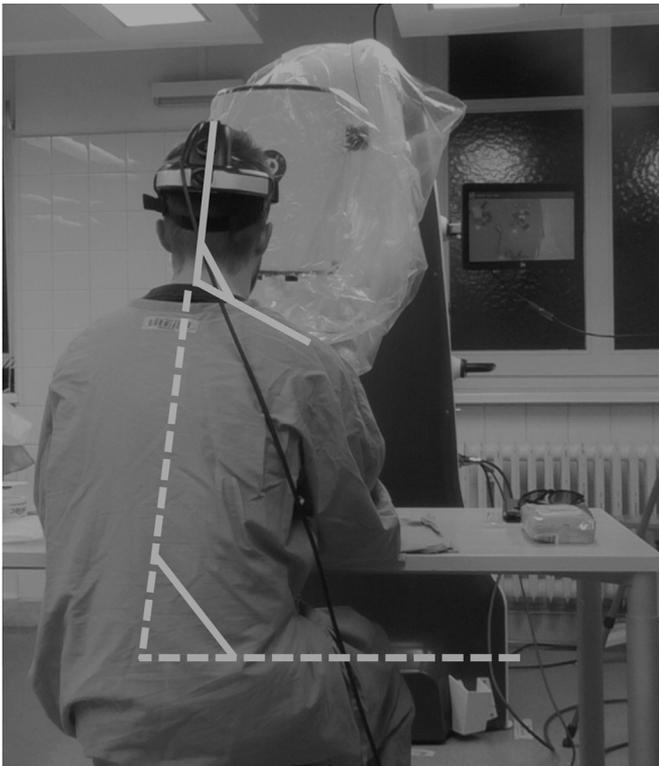
The majority of participants showed minor median displacement of the upper body from the neutral axis (Fig. 5) with  $0^\circ$  [IqR -3, 5], the median head accounted for  $0^\circ$  [IqR 0, 2]. The statistical analysis revealed a significant correlation of low head/body displacement and less time ( $p = 0.019$ ) for the conduction of the exercise. The more experienced participants showed significant more head tilt starting at  $20^\circ$  ( $p = 0.01$ ,  $r = 0.48$ ) and the influence on movement of the RS was significant starting at  $25^\circ$  of tilt ( $p = 0.035$ ,  $r = -0.42$ ). Participants with less body shift also reported of significant less difficulties for the operation of the RS (starting at body tilt  $>10^\circ$ ,  $p = 0.038$ ,  $r = 0.43$ ). A higher degree of head/body shift was significantly associated with a reduced number of head repositioning while performing a single command, such as tilting the RS (starting at head tilt  $>25^\circ$ ,  $p = 0.035$ ,  $r = -0.44$ ).

## 4. Discussion

The aim of this study was to investigate usability, ergonomics and

neurosurgeon's comfort of the novel three-dimensional HMD-based exoscope. We demonstrated that a robot-controlled exoscope with head-mounted displays and gesture controls can be used comfortably for microsurgery and that introduction and exercise are not time consuming in comparison to a classical operating microscope. Despite the constant development of new technologies, the basic design of the surgical microscope with eyepieces is widely used and has remained close to its original development. Due to the unergonomic position that microsurgery often requires, long-term health of surgeons as well as the optimal surgical outcomes for patients are at higher risk. A recent questionnaire has shown reduced concentration and surgical speed in roughly 20% of microsurgeons, due to long-term procedures using conventional microscopes (Howarth et al., 2018). About 8% of the surgeons experienced increased tremor due to the discomfort and 29% received medical treatment due to WMSDs (Howarth et al., 2018). The use of a HMD allows a rather neutral head position to gain a more comfortable posture for the surgeon notwithstanding the camera position.

During the conduction of this study, the participants reported an intuitive handling of the RS supported by the simple user interface. As a



**Fig. 5.** Analysis of body and head posture during the exercise. The reference points were set at the uppermost point of the head, the coronal rotational center of the neck and the right shoulder for head movement. Upper body movement was measured as the angle between the horizontal, the lumbosacral spine as well as the coronal rotational center of the neck.

consequence, the majority of the participants would continue to use the RS in the operating room. The desire for technical assistance can be explained with the novelty of the device and the high quality standards of neurosurgeons. Due to the lack of experience with using the RS, some participants reported dizziness and discomfort while using the HMD. This may be due to the unusual weight of the HMD (approximately 500 g) as well as the cable, which connects the HMD to the RS. During the study, the technical assistance primarily served to optimize the visual quality and the appropriate positioning of the HMD. Nevertheless, this finding is contrary to previous studies, reporting only 58.9% of the surgeons willing to use monitor-based exoscopes in the OR (Rösler et al., 2021). The pre-interventional assisted training of 30 min was sufficient enough to minimize the median number of operating errors to only two, hence a safe transition of this technique into the operating room could be performed with minimal effort. The image quality as a fundamental parameter in microsurgical operations was reported with a median of 82% overall satisfaction. An optimal adjustment of the HMD even prior to the start of the exercise is key to achieve high satisfaction with the visual quality. On the contrary, users reported that HMD needed to be repositioned during the course of the exercise due to misaligned position of the displays, which could cause dizziness and even nausea. The weight of the HMD should also decrease over time as these inputs may serve as an impulse for a future improvement of the RS and HMD. The user friendliness of the RS interface as well as the possibility to train the relevant commands using a simple microsurgical tool offers excellent conditions for a safe and swift transition towards the exoscope.

Although we discovered a steep learning curve in the majority of the study participants, there was a significant higher efficiency in participants with previous video game exposure and/or low microsurgical experience. Consequently, participants with video game experience described the RS as even easier to use than those without video game

experience. This group also performed significantly better with regard to operating errors and felt more secure than participants with no video game history or a longer experience using a conventional microscope.

Using the custom-made microsurgical skill training tool, the authors were able to perform a quantitative assessment of the surgeons' skills using the RS. The microsurgical training tool has not only shown as an efficient method for dexterity training but is also an effective method to train the most important micro- or exoscopic commands which are needed in the OR. The model used here allows conclusions to be drawn regarding the learning curve for usability, since a large number of commands and settings were required to switch between eyelets one through ten.

The advantage of head-mounted displays allows a neutral position during surgery, thereby potentially reducing WMSDs and allowing surgeons a more focused and precise handling of the surgical area. The results of this study showed a median head and body displacement amounting to 0°, meaning the participants stayed in a neutral position during the majority of the training session. This finding is in accordance with previous studies reporting a significantly improved surgeons' comfort using monitors instead of oculars (Roethe et al., 2020). Neurosurgical residents with low microscope experience and interns have shown even less head/body displacement which underpins the simple applicability of this novel device. Previous studies comparing conventional with monitor-based microscopes showed a 91.7% preference of the surgeons for the use of monitor-based models (Eckardt and Paulo, 2016). The risk for WMSDs is especially high in (micro-)surgical specialties with a chronic pain incidence of up to 40% (Howarth et al., 2018; Lakhiani et al., 2018; Yu et al., 2012, 2016; Franken et al., 1995; Gorman et al., 2001; Wong et al., 2014; Mendez et al., 2016). Recent findings showed a fourfold increase of weight in case of a 30° neck flexion which could explain the negative impact of chronic microscope usage for the career duration of neurosurgeons (Hansraj, 2016). Display-based exoscopes could therefore play a major key role in the prevention of WMSD-related sick leave, especially in surgeons with high operative caseloads.

## 5. Limitations

This study includes several limitations which reduce the validity of the results. Due to the relatively short duration of the run (12 min), side effects potentially occurring during surgical procedures lasting for several hours could not be recorded. This will require further clinical or cadaver studies. The ability to assess image quality may be reduced in participants with limited microsurgical experience due to lack of comparison with conventional microscopes. The questionnaires were mainly based on 5-point Likert scales which may not allow a detailed itemization of the participants' satisfaction with the RS.

## 6. Conclusion

The robot-controlled exoscope has shown as a novel approach with favorable contentment of experienced as well as young neurosurgeons. Image quality as well as exoscope handling were reported to be sufficient, thereby providing a safe and easy transition of the RS into the operating room. The custom-made microsurgical tool proved as an efficient method for training the relevant commands of the robotic arm. Using the RS, the participants had a neutral posture, which may lead to less work-related musculoskeletal disorders in the long-term.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.bas.2021.100855>.

## References

- Amoo, M., Henry, J., Javadpour, M., 2021. Beyond magnification and illumination: preliminary clinical experience with the 4K 3D ORBEYE™ exoscope and a literature review. *Acta Neurochir.* <https://doi.org/10.1007/s00701-021-04838-8>.
- Auerbach, J.D., Weidner, Z.D., Milby, A.H., Diab, M., Lonner, B.S., 2011. Musculoskeletal disorders among spine surgeons: results of a survey of the scoliosis research society membership. *Spine* 36 (26). <https://doi.org/10.1097/BRS.0b013e31821cd140>.
- Eckardt, C., Paulo, E.B., 2016. Heads-up surgery for vitreoretinal procedures : an experimental and clinical study. *Retina* 36 (1), 137–147. <https://doi.org/10.1097/IAE.0000000000000689>.
- Figueiredo, N., Katherine, E.T., Sunil, K.S., et al., 2020. Conventional microscope-integrated intraoperative OCT versus digitally enabled intraoperative OCT in vitreoretinal surgery in the discover study. *Ophthalmic Surg. Lasers Imaging Retin.* 51 (4), S37–S43. <https://doi.org/10.3928/23258160-20200401-05>.
- Franken, R.J.P.M., Gupta, S.C., Banis, J.C., et al., 1995. Microsurgery without a microscope: laboratory evaluation of a three-dimensional on-screen microsurgery system. *Microsurgery* 16 (11), 746–751. <https://doi.org/10.1002/micr.1920161109>.
- Gonen, L., Chakravarthi, S.S., Monroy-Sosa, A., et al., 2017. Initial experience with a robotically operated video optical telescopic-microscope in cranial neurosurgery: feasibility, safety, and clinical applications. *Neurosurg. Focus* 42 (5), E9. <https://doi.org/10.3171/2017.3.FOCUS1712>.
- Gorman, P.J., Mackay, D.R., Kutz, R.H., Banducci, D.R., Haluck, R.S., 2001. Video microsurgery: evaluation of standard laparoscopic equipment for the practice of microsurgery. *Plast. Reconstr. Surg.* 108 (4), 864–869. <https://doi.org/10.1097/00006534-200109150-00008>.
- Hansraj, K.K., 2014. Assessment of stresses in the cervical spine caused by posture and position of the head. <https://doi.org/10.1016/j.pain.2014>.
- Helayel, H Bin, Al-Mazidi, S., AlAkeely, A., 2021. Can the three-dimensional heads-up display improve ergonomics, surgical performance, and ophthalmology training compared to conventional microscopy? *Clin. Ophthalmol.* 15, 679. <https://doi.org/10.2147/OPHT.S290396>.
- Herlan, S., Marquardt, J.S., Hirt, B., Tatagiba, M., Ebner, F.H., 2019. 3D exoscope system in neurosurgery-comparison of a standard operating microscope with a new 3D exoscope in the Cadaver Lab. *Oper. Neurosurg.* 17 (5). <https://doi.org/10.1093/ons/opz081>.
- Howarth, A.L., Hallbeck, S., Mahabir, R.C., Lemaine, V., Evans, G.R.D., Noland, S.S., 2018. Work-related musculoskeletal discomfort and injury in microsurgeons. *J. Reconstr. Microsurg.* 35, 322–328. <https://doi.org/10.1055/S-0038-1675177>, 05.
- Lakhiani, C., Fisher, S.M., Janhofer, D.E., Song, D.H., 2018. Ergonomics in microsurgery. *J. Surg. Oncol.* 118 (5), 840–844. <https://doi.org/10.1002/JSO.25197>.
- Lavé, A., Gondar, R., Demetriades, A.K., Meling, T.R., 2020. Ergonomics and musculoskeletal disorders in neurosurgery: a systematic review. *Acta Neurochir.* 162 (9). <https://doi.org/10.1007/s00701-020-04494-4>.
- Mamelak, A.N., Nobuto, T., Berci, G., 2010. Initial clinical experience with a high-definition exoscope system for microneurosurgery. *Neurosurgery* 67 (2). <https://doi.org/10.1227/01.NEU.0000372204.85227.BF>.
- Mendez, B.M., Chiodo, M.V., Vandevender, D., Patel, P.A., 2016. Heads-up 3D microscopy: an ergonomic and educational approach to microsurgery. *Plast. Reconstr. Surg. - Glob Open.* 4 (5). <https://doi.org/10.1097/GOX.0000000000000727>.
- Oertel, J.M., Burkhardt, B.W., 2017. Vitom-3D for exoscopic neurosurgery: initial experience in cranial and spinal procedures. *World Neurosurg.* 105. <https://doi.org/10.1016/j.wneu.2017.05.109>.
- Park, J.Y., Kim, K.H., Kuh, S.U., Chin, D.K., Kim, K.S., Cho, Y.E., 2012. Spine surgeon's kinematics during discectomy according to operating table height and the methods to visualize the surgical field. *Eur. Spine J.* 21 (12). <https://doi.org/10.1007/s00586-012-2425-6>.
- Ricciardi, L., Chaichana, K.L., Cardia, A., et al., 2019. The exoscope in neurosurgery: an innovative "point of view." A systematic review of the technical, surgical, and educational aspects. *World Neurosurg.* 124. <https://doi.org/10.1016/j.wneu.2018.12.202>.
- Roethe, A.L., Landgraf, P., Schröder, T., Misch, M., Vajkoczy, P., Picht, T., 2020. Monitor-based exoscopic 3D4k neurosurgical interventions: a two-phase prospective-randomized clinical evaluation of a novel hybrid device. *Acta Neurochir.* 162 (12). <https://doi.org/10.1007/s00701-020-04361-2>.
- Rösler, J., Georgiev, S., Roethe, A.L., et al., 2021. Clinical implementation of a 3D4K-exoscope (Orbey) in microneurosurgery. *Neurosurg. Rev.* 1, 1–9. <https://doi.org/10.1007/S10143-021-01577-3>, 2021.
- Schär, M., Rösli, C., Huber, A., 2021. Preliminary experience and feasibility test using a novel 3D virtual-reality microscope for otologic surgical procedures. *Acta Otolaryngol.* (1), 141. <https://doi.org/10.1080/00016489.2020.1816658>.
- Siller, S., Zoellner, C., Fuetsch, M., Trabold, R., Tonn, J.C., Zausinger, S., 2020. A high-definition 3D exoscope as an alternative to the operating microscope in spinal microsurgery. *J. Neurosurg. Spine* 33 (5). <https://doi.org/10.3171/2020.4.SPINE20374>.
- Uluç, K., Kujoth, G.C., Başkaya, M.K., 2009. Operating microscopes: past, present, and future. *Neurosurg. Focus* 27 (3). <https://doi.org/10.3171/2009.6.FOCUS09120>.
- Weinstock, R.J., Ainslie-Garcia, M.H., Ferko, N.C., et al., 2021. Comparative assessment of ergonomic experience with heads-up display and conventional surgical microscope in the operating room. *Clin. Ophthalmol.* 15, 347. <https://doi.org/10.2147/OPHT.S292152>.
- Wong, A.K., Davis, G.B., Joanna Nguyen, T., et al., 2014. Assessment of three-dimensional high-definition visualization technology to perform microvascular anastomosis. *J. Plast. Reconstr. Aesthetic Surg.* 67 (7), 967–972. <https://doi.org/10.1016/j.bjps.2014.04.001>.
- Yu, D., Sackllah, M., Woolley, C., Kasten, S., Armstrong, T., 2012. Quantitative posture analysis of 2D, 3D, and optical microscope visualization methods for microsurgery tasks. *Work* 41, 1944–1947. <https://doi.org/10.3233/WOR-2012-0412-1944>.
- Yu, D., Green, C., Kasten, S.J., Sackllah, M.E., Armstrong, T.J., 2016. Effect of alternative video displays on postures, perceived effort, and performance during microsurgery skill tasks. *Appl. Ergon.* 53, 281–289. <https://doi.org/10.1016/j.apergo.2015.10.016>.