A Virtual Repository of Neurosurgical Instrumentation for Neuroengineering Research and Collaboration

Ramandeep Singh[1], *Britty Baby*[2], *Ashish Suri*[1]

■ BACKGROUND: **Advancements in microscopy and more recently in neuroendoscopy have revolutionized the field of neurosurgery. Handheld neurosurgical instruments are integral components of these procedures. However, these instruments have many limitations, such as poor ergonomics, constrained maneuverability, and limited degrees of freedom. A need for developing better instruments is commonly felt by neurosurgeons. Also, the focus of modern neurosurgical training is shifting toward simulation models. The baseline data of surgical instruments play a vital role in the development of virtual and physical simulators. A primary factor impeding development of novel instruments and simulators is lack of a comprehensive surgical instrument database. The aim of this study was to develop and validate a virtual repository of microscopic and neuroendoscopic instruments.**

■ METHODS: **Standard neurosurgical instrument sets were scanned, reverse engineered, and stored in various file formats at the file transfer protocol server. The developed database was validated by 4 groups of experts by creating different neurosurgery applications.**

■ RESULTS: **Four groups of experts used the repository content to create novel ergonomic instrument designs, e-learning material, computer vision–based surgical skills evaluation and virtual reality and validated the contents. The validation results showed that quality of content (75%), usefulness of content (85.6%), and time saving using content (88.1%) received high scores, and the effectiveness of the virtual repository contents was appreciated.**

■ CONCLUSIONS: **The virtual database is an efficient starting aid to foster research collaborations related to neurosurgical instruments and surgical simulation platforms.**

INTRODUCTION

Neurosurgery as a surgical specialty deals with diseases of the central nervous system. At the present time, most neurosurgical procedures are performed using an operating microscope or a rigid endoscope or both. Operating microscopes provide stereoscopic vision and high magnification. In contrast, neuroendoscopy provides a display of the surgical site on two-dimensional monitors or on recently introduced three-dimensional (3D) monitors.[1,2] In both techniques, a variety of neurosurgical instruments are used to facilitate various surgical tasks.[3] There have been significant technological advancements in microscopes and endoscopes, particularly in terms of optics and user interface. However, neurosurgeons are not satisfied with today's rigid neurosurgical instruments owing to poor ergonomics, limited degrees of freedom, dexterity constraints, single function, and small operating corridor.[4,5]

The development of improved and better instruments requires baseline data of these complex and fine instruments. Access to neurosurgical instruments is difficult owing to concerns regarding their effectiveness and sterility. A primary factor impeding research related to the development of new instruments is the lack of a virtual database of instrument dimensions, designs, and mechanisms. Neurosurgery simulations are another area of research that demands baseline data of instruments. Simulation-based training has

Key words
- Blue light scanning
- Innovation
- Neurosurgical instruments
- Reverse engineering
- Simulation
- Virtual repository

Abbreviations and Acronyms
3D: Three-dimensional
CAD: Computer-aided designing
STL: Stereolithography

From the [1]*Department of Neurosurgery, All India Institute of Medical Sciences, New Delhi; and* [2]*Amar Nath and Shashi Khosla School of Information Technology, Indian Institute of Technology Delhi, New Delhi, India*

To whom correspondence should be addressed: Ashish Suri, M.B.B.S., M.Ch. [E-mail: surineuro@gmail.com]

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Table 1. Functional Classification of Microscopic and Neuroendoscopic Instruments

Microscopic Instruments		Neuroendoscopic Instruments (Endonasal)		Neuroendoscopic Instruments (Ventricular)	
Category	**Instrument**	**Category**	**Instrument**	**Category**	**Instrument**
Elevators	Periosteal elevator single ended	Telescopes and vision system	Telescopes straight forward (0°), forward oblique (30°, 45°)	Telescopes and vision system	Telescopes straight forward (0°), forward oblique (30°, 45°)
	Periosteal elevator double ended		Endoscope sheath, suction and irrigation sheath		Operating sheath, endoscope sheath, suction and irrigation sheath
					Hollow obturator
					Endoscope holder, rotation socket, articulated stand, clamping jaw
Forceps	Micro forceps straight	Probes and elevators	Double ended maxillary sinus ostium seeker	Flexible operating instruments	Biopsy forceps double action jaw
	Micro forceps curved		Double ended blunt end angled semisharp end elevator		Scissors pointed/blunt single action jaw
	Micro forceps for grasping tissues		Sickle knife pointed		Grasping forceps double action jaw
	Microsuture tying forceps				Ventriculostomy forceps
	Forceps micro jeweler's straight				Injection needle
	Forceps micro long				Ball electrode
	Forceps micro straight				Spatula-shaped electrode
	Forceps nontoothed				
	Forceps toothed				
	Delicate dissecting forceps				
	Tissue forceps				
Scissors	Micro scissors straight	Forceps	Nasal dressing bayonet shaped		
	Micro scissors bayonet shaped		Nasal cutting		
	Micro scissors bayonet straight blade		Nasal forceps		
	Micro scissors bayonet curved blade		Nasal forceps 45° upturned		
	Metzenbaum scissors straight		Ethmoid forceps		
	Metzenbaum scissors curved				
Needle holder	Microneedle holder straight	Scissors	Nasal scissors straight		
	Microneedle holder bayonet shaped		Nasal scissors curved to right		

Continues

Table 1. Continued

Microscopic Instruments		Neuroendoscopic Instruments (Endonasal)		Neuroendoscopic Instruments (Ventricular)	
Category	**Instrument**	**Category**	**Instrument**	**Category**	**Instrument**
	Microneedle holder with round handles		Nasal scissors curved to left		
Bone punches	Straight footplate up cut	Punches	Micro-punch up-biting		
	Thin footplate up cut		Micro-punch down-biting		
	Straight footplate down cut		Antrum punch		
	Thin footplate down cut				
Ronguer	Up cut	Raspatories, scalpels	Scalpel with retractable blade		
	Down cut		Micro raspatory curved left		
	Bone ronguer				
Retractors	Self-retaining retractors	Curette	Round spoon straight		
			Round spoon slightly angled		
Curette	Round spoon straight	Dissectors	Dead hand bayonet shaped		
	Round spoon angled				
	Pituitary curette				
Dissectors	Micro dissector				
	Bayonet shaped curved upward				
	Bayonet shaped curved downward				
	Micro-hook				
Probes and elevators	Light source, suction and irrigation probes, periosteal elevator				
Knifes and scalpels	Round knife				
	Knife BP handle				
	Pick bayonet shaped				
	Handles flat and round				
	Blades				

emerged as a powerful learning tool in the era of minimally invasive neurosurgery.[6] With the technological advancements in computer graphics, stereoscopic screens, haptics, and 3D printing, a variety of simulation modules are being developed for training and evaluation of neurosurgical skills. Most simulators are virtual reality simulators and physical or synthetic simulators.[7,8] The main components of a virtual simulator include a haptic user interface, virtual models of anatomic structures, and surgical instruments.[9] Other research areas that use such a database include computer vision–based surgical skill assessment and neurosurgical e-learning platforms.[10,11]

The shape of surgical instruments involves complex contours, and their manual measurement may lead to dimensional errors. Contact-free 3D surface scanning techniques give accurate dimensions as surface models. Commercially available scanners appropriate for this purpose are structured light scanners and laser scanners. Structured light scanners are based on stripe projection of light patterns and laser scanners on line projection of class 2 laser source.[12] Structured light or blue light scanners use programmed turning table and result in fewer manual errors in measurement, whereas laser scanners have a handheld probe and require expert manpower to accomplish accurate measurements. Blue light scanners are more appropriate to scan neurosurgical instruments.[13] Reverse engineering is performed on the scanned data to create virtual models. It includes extraction of 3D curves from the scanned data and interpolation of surfaces to create solid models.[14]

The aim of the present study was development and validation of a virtual repository of microscopic and neuroendoscopic instruments to assist in creation of neurosurgery simulation models and novel instruments. The significance of the developed repository was established by using it for various applications. The repository was validated by 4 groups of experts, including computer-aided designers, animators, computer vision programmers, graphics programmers, and neurosurgeons. Results show that the virtual repository is a significant resource to conduct research related to neurosurgical instruments for neuroengineering research and collaboration.

MATERIALS AND METHODS

The development of the virtual repository involved functional classification, blue light scanning, reverse engineering, storage framework, and validation.

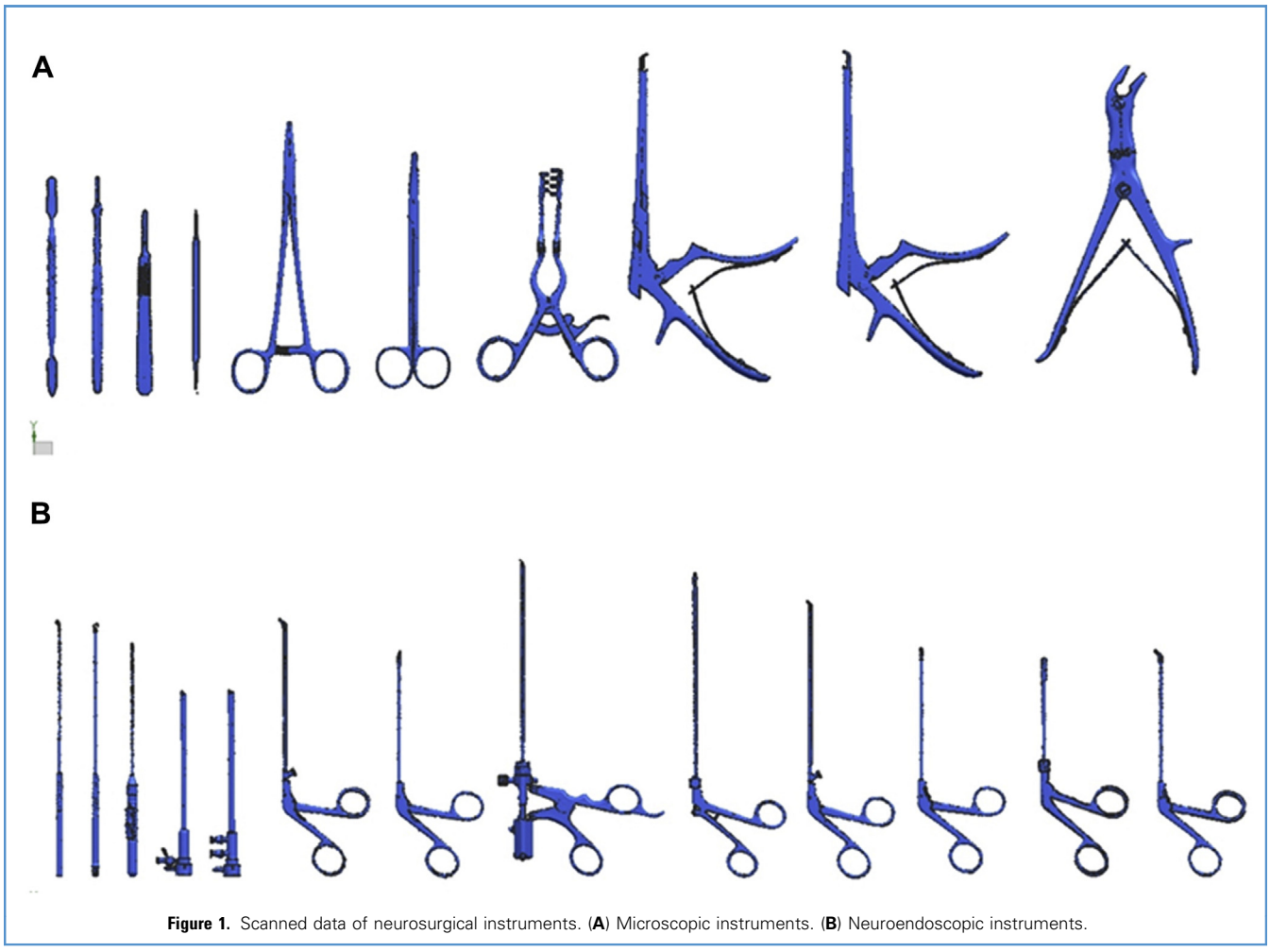

Figure 1. Scanned data of neurosurgical instruments. (**A**) Microscopic instruments. (**B**) Neuroendoscopic instruments.

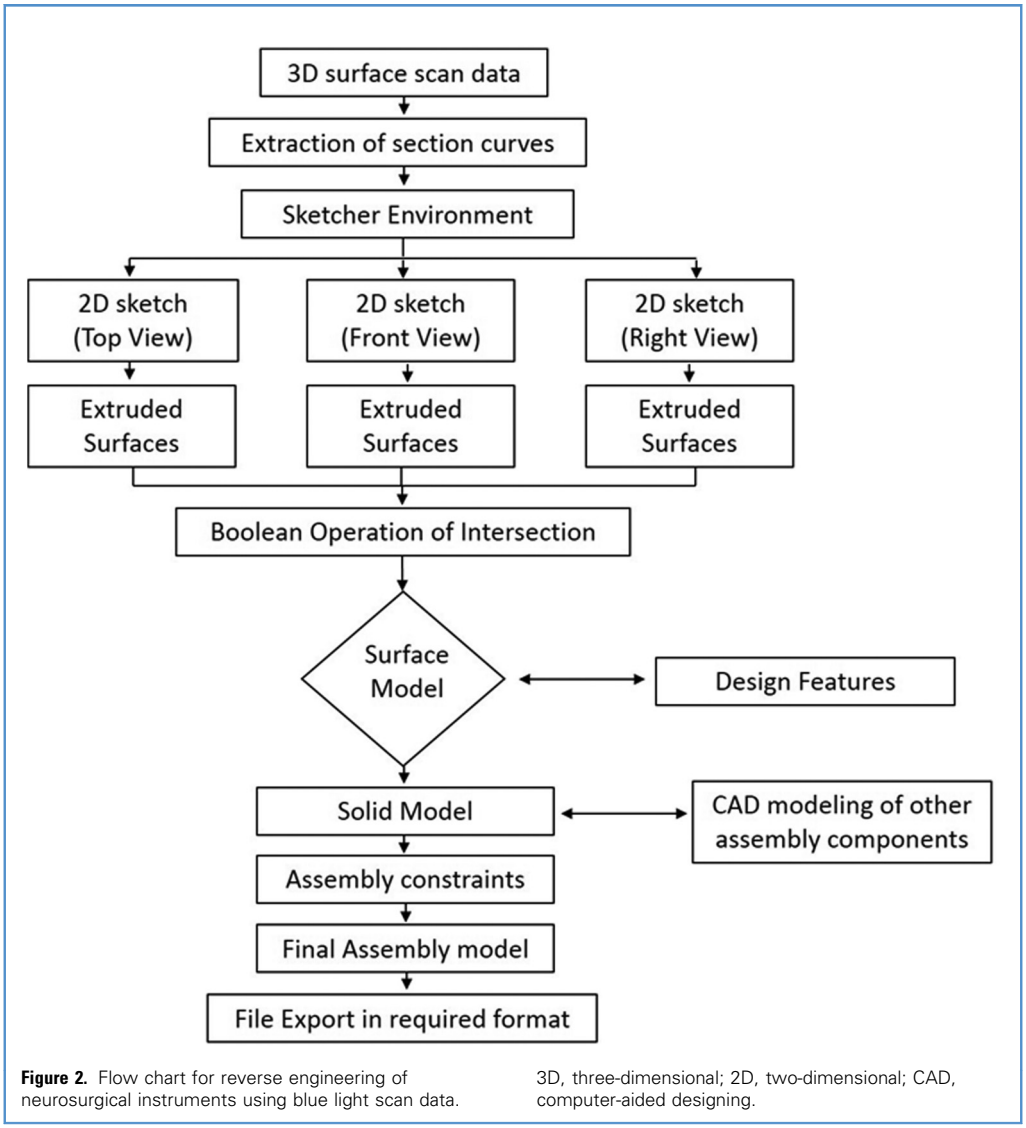

Figure 2. Flow chart for reverse engineering of neurosurgical instruments using blue light scan data. 3D, three-dimensional; 2D, two-dimensional; CAD, computer-aided designing.

Classification

The set of instruments used for neurosurgery varies according to operating method, surgical approach, and surgeon's preference. The first step of development of the repository was structured classification of these instruments. The instrument function and surgical technique were taken as the primary criteria for classification. The instruments were classified into various categories based on functionality (e.g., cutting or incising, retracting, grasp or hold, dilating). The instruments were likewise ordered into microscopic, neuroendoscopic endonasal, and neuroendoscopic ventricular instruments (Table 1).

Blue Light Scanning

The surface information of all the instruments was procured using a Steinbichler Comet L3D 2 Megapixel blue light 3D scanner (Carl Zeiss AG, Oberkochen, Germany). Instruments were placed on the programmed rotary table, and data were captured using a rotation angle of 60°. The Comet-PLUS software (Carl Zeiss AG, Oberkochen, Germany) was then used to merge the scans captured from different orientations. Noise reduction, filtering, and gap filling operations were applied to the merged data, and stereolithography (STL) files were created. Figure 1 shows the scanned data of some microscopic and neuroendoscopic instruments.

Table 2. Questionnaire to Validate Developed Virtual Repository

Question	Criteria for Assessment
1	Access to content
2	Quality of content
3	Usefulness of content
4	Time saving using content

Figure 3. Ergonomic improvement of neurosurgery instruments. (**A**) Computer-aided designing model of micro forceps. (**B**) Computer-aided designing model of modified micro forceps.

Reverse Engineering

Unigraphics NX computer-aided designing (CAD) software (Siemens PLM Software, Plano, Texas, USA) was used for reverse engineering of scanned instruments. The STL file of blue light–scanned data was imported and aligned to the coordinate system. The two-dimensional sketch in each view (top, side, and front) was prepared in the sketcher environment of CAD software. These sketches were then interpolated into surfaces, and boolean operation of the intersection was applied to extract the shape of the instrument. These surfaces were then converted into a 3D solid model, and various design features were applied. A flow chart of the process is shown in Figure 2.

Storage Framework

The developed CAD models were stored in the Netapp/FAS2240 file transfer protocol server. The content of repository can be accessed through the Neurosurgery Education and Training School local area network path (\\192.168.1.5\nets60\Repository). It includes 2 folders named "microscopic instruments" and "neuroendoscopic instruments." It contains subfolders for microscopic, neuroendoscopic endonasal, and neuroendoscopic ventricular instruments. Finally, the models are stored into 6 categories based on their function. Each folder contains the CAD file (.prt), STL (.stl) file, object (.obj) file, parasolid (x_t) and motion simulation video in movie (.mov) format. A repository of 66 microscopic and neuroendoscopic instruments has been developed.

Validation of Repository

The repository was designed by biomedical engineers in collaboration with neurosurgeons for defining neurosurgery applications. Subsequently, the significance of the developed repository was established by an external group of experts. Four groups of experts used the virtual repository to create various neurosurgery applications. The expert groups included computer-aided designing specialists, animation specialists, graphics programmers, and computer vision programmers with 4 experts in each group. They used the content for creating novel instruments, surgical procedure simulation, computer vision–based skills evaluation, and virtual reality simulation. A Likert-type scale questionnaire (Table 2) was formulated for validation, and expert groups gave scores of 1–10 for each parameter in the questionnaire. The

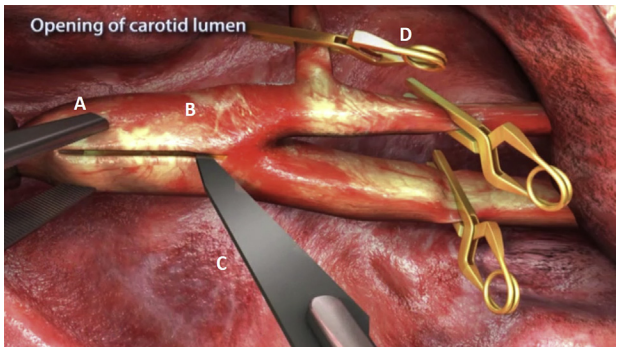

Figure 4. E-learning content to demonstrate the procedure of carotid endarterectomy in microneurosurgery. (**A**) Forceps. (**B**) Surgical blade. (**C**) Carotid lumen. (**D**) Aneurysm clips.

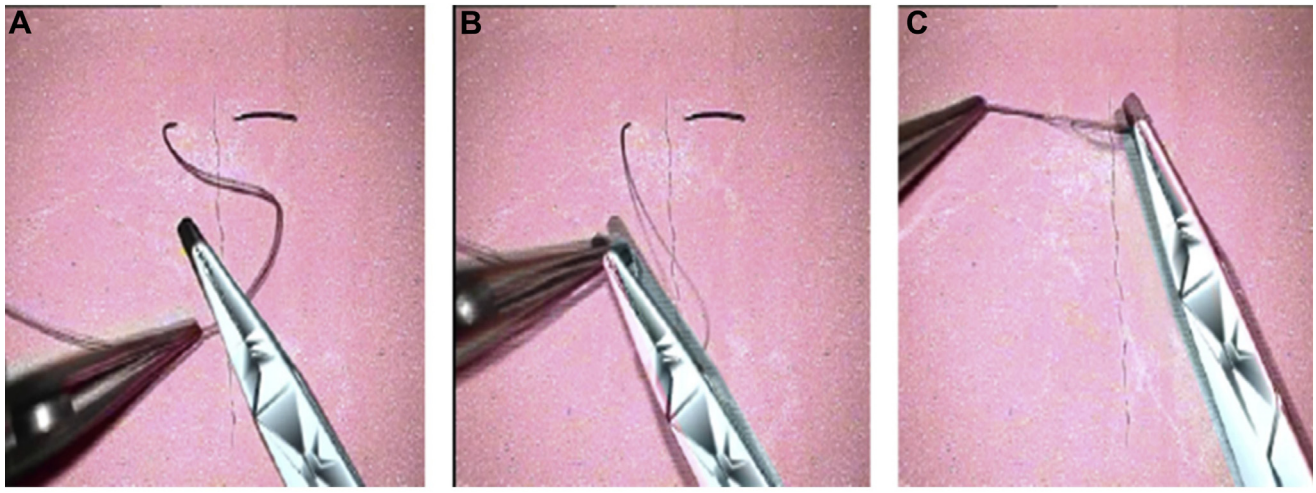

Figure 5. Frame-by-frame tracking of the surgical instrument with an overlapped three-dimensional model during microsuturing task on Silastic sheet. (**A**) Suture holding. (**B**) Pulling loop. (**C**) Knot tying.

higher the score obtained in the Likert-type scale, the better was the valuation (1 is the least and 10 is the highest score). The ordinal scores from 4 groups of experts were tabulated in Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and were compared using bar plots.

RESULTS

A virtual repository of 66 microneurosurgical and neuroendoscopic instruments was developed. To gauge the need of service provided to the research community, we evaluated the utilization of the virtual repository in 4 different areas of neuroengineering.

Novel Instrument Designing

The repository was used for validation of prototype development methods and creation of novel ergonomic design of one microscopic instrument.[15,16] Micro forceps, a commonly used instrument for suturing tasks in microneurosurgery, was modified to better adapt for usage under high magnification. The inter-tip distance was reduced and the length of the instrument was increased according to surgeon's feedback (Figure 3).

E-Learning in Neurosurgery

The virtual repository was used for creating content for e-learning in neurosurgery. The virtual models of instruments were used in carotid endarterectomy animation (Figure 4). Based on reference neurosurgical images, expert neurosurgical operation videos, textbooks, and input from senior fellows and expert neurosurgeons, the digital content was created.

Computer Vision–Based Surgical Skills Evaluation

Computer vision–based surgical skill analysis was performed using the 3D models of instruments. The 3D model fitting was performed on the video for appropriate positioning or registering of the instrument based on its pose. This involves extracting image features such as edges, points, or regions and then solving alignment cost functions, which measure the agreement with parametrized models of the tool. Figure 5 shows the frame-by-frame tracking of the surgical instrument with an overlapped 3D model.

Virtual Reality Simulation

The virtual model of surgical instruments was registered with the haptic interface. A CHAI3D simulation framework (http://www.chai3d.org/) was used to establish a visual-haptic interface between the virtual anatomic models and the surgical instrument. The virtual anatomic models were volumetric data obtained from

Figure 6. Virtual reality simulation. (**A**) Virtual model of skull. (**B**) Curette. (**C**) Haptic device. (**D**) Stylus.

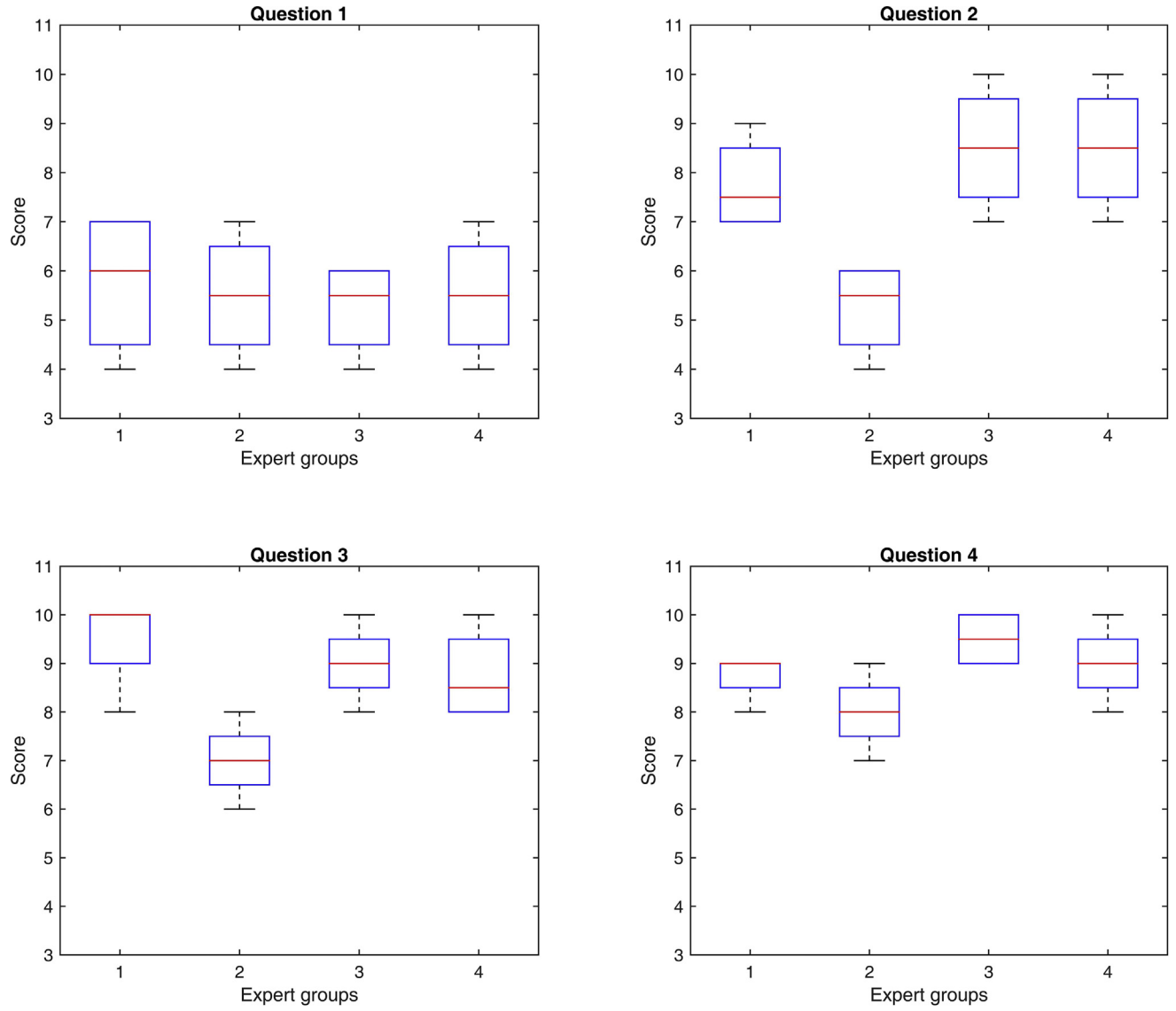

Figure 7. Validation results based on feedback from expert groups 1–4 (computer-aided designing specialists, animation specialists, graphics programmers, and computer vision programmers respectively) after using repository content.

computed tomography and magnetic resonance imaging datasets. A monolithic instrument (spoon curette) was used to interact with the anatomic model. A reaction force and torque model were obtained based on physical characteristics of the virtual instrument to provide real-time haptic feedback to the user (Figure 6).

Validation

The repository was used for various neurosurgery applications, and experts in the related field validated the content. The scores given by expert groups were averaged. Access to the repository content was given 55% marks, owing to on-demand access for being an institutional repository. Quality of the content received 75% marks; CAD experts gave the comments that the tips of some sharp instruments were not scanned properly in the STL files. However, the CAD models were found to be of superior quality. Usefulness of content was given 85.6% marks, and time saving using the content was given 88.1% marks. Figure 7 shows the box plots for comparison of scores from 4 groups for each question.

The validation shows that the repository is a promising tool for neurosurgical innovation and simulation. Access to the content can be improved by providing online access to the content. The quality of the scanned data at the tips of fine instruments can be

improved by using a higher version of the blue light scanner with a smaller field of view lens.

DISCUSSION

Online databases provide a comprehensive resource to structure and share data among researchers. Repositories available in the medical field include biomedical signals, biomedical images, anatomic structures, genome sequences, gait data, protein structures, and drug structures.[17-20] These repositories provide an efficient source of conducting research and validation of algorithms. However, databases related to virtual 3D models of surgical instruments are lacking. If the primary objective is to conduct research related to neurosurgical instruments, the repeated development of virtual models will lead to wastage of resources. Hence, a structured solution of virtual models of neurosurgical instruments can be of significant importance to the current digital scenario. The present study provides an insight to the development of high-quality virtual models of fine neurosurgical instruments and structured deposit of content for efficient access. The same methodology can be applied for deposit of additional neurosurgical instruments as well as instruments of other surgical specialities. The virtual models are arranged based on surgical technique, structure, and functionality. The developed repository is a research repository that can be accessed on demand for research purposes.

The files are preserved in various data formats according to specific applications. The .prt format contains modifiable models with individual components along with a reverse engineering history tree, which can be edited with rollback. The STL file format is standard for additive manufacturing or 3D printing and contains information regarding facets and vertices. Object (.obj) files contain information regarding triangulated faces and texture. This format is commonly used for creating virtual simulations. Parasolid (x_t) file can be imported in standard CAD packages and can be edited. The repository does not provide access to intermediate models created by scanned data. This is due to the fact that even the advanced scanning methods cannot reproduce the complete model of these fine neurosurgical instruments, especially at the tips. Most neurosurgical instruments comprise various subparts that need to be modeled individually to create the functional assembly. Therefore, scanned data cannot be used directly, and reverse engineering is an essential step. The average time for blue light scanning, reverse engineering, exporting all required file formats, and storage was 3 days (8 hours/day) for each instrument, with every activity requiring specific skilled manpower.

We have demonstrated various applicable areas of the developed repository. The service provided by the repository can be used by researchers working in translational research areas. The service of the developed repository can be extended to many technologically impending areas, such as development of multiple degrees of freedom instruments, multifunctional instruments, micromanipulators, and sensor-based smart instruments.

CONCLUSIONS

A virtual repository of existing microscopic and endoscopic neurosurgical instruments has been created. The developed virtual models were used for various applications, such as novel instrument development, e-learning, computerized evaluation of surgical skills, and virtual reality simulations. A current research repository is more sustainable if it is converted to a multi-institutional repository inclusive of the academic community. It can have a function as a depot for student research and can lead to increased acceptance with a focus toward public access. The repository is scalable and can be mirrored with institutional collaborations. Such a repository has high potential for conducting research related to neurosurgery innovation and simulation.

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