NEUROSURGICAL
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Supplemental material

A systematic review of virtual reality for the assessment of technical skills in neurosurgery

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https://thejns.org/doi/abs/10.3171/2021.5.FOCUS21210

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Supplemental Table 1

Author, Year	Participants	Procedure (System)	Salient Point(s)
Banerjee et al., 2007[1]	78 (18F, 60R)	ventriculostomy (ImmersiveTouch)	In large, increasing PGY is associated with better trajectories that lead to lower distances to targets. More frequent practice sessions do increase these performance metrics, and if not, a loss in accuracy may occur.
Lemole et al., 2009[2]	48 (48R)	ventriculostomy (ImmersiveTouch)	
Schirmer et al., 2013[3]	14 (14 F/R†)	ventriculostomy (ImmersiveTouch)	
Shakur et al., 2015[4]	71 (71R)	percutaneous rhizotomy (ImmersiveTouch)	
Perin et al., 2018[5]	92 (18A, 74R)	ventriculostomy (ImmersiveTouch)	
Luciano et al., 2011[6]	51 (51 F/R†)	thoracic pedicle screw placement (ImmersiveTouch)	
Luciano et al., 2013[7]	63 (63 F/R†)	percutaneous spinal needle placement (ImmersiveTouch)	
Yudkowsky et al., 2013[8]	16 (16R)	ventriculostomy (ImmersiveTouch)	
Bajunaid et al., 2017[9]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	The role of distance to a target can serve as an indicator for both accuracy and efficiency of motion. In all articles using machine learning and artificial intelligence, distance to target APMs were included.
Azarnoush et al., 2015[10]	2 (1A, 1R)	brain tumor resection (NeuroTouch)	
Winkler-Schwartz et al., 2016[11]	16 (16M)	brain tumor resection (NeuroTouch)	
Gélinas-Phaneuf et al., 2014[12]	72 (62R, 10M)	brain tumor resection (NeuroTouch)	
AlZhrani et al., 2015[13]	33 (17A, 16R)	brain tumor resection (NeuroTouch)	
Siyar et al., 2020[14]	115 (16A, 15R, 84M)	brain tumor resection (NeuroTouch)	
Bugdadi et al., 2019[15]	6 (6A)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[17]	16 (16M)	brain tumor resection (NeuroVR)	
Mirchi et al., 2020[18]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Bissonnette et al., 2019[19]	41 (41R)	hemilaminectomy (NeuroVR)	
Burström et al., 2019[20]	2 (2A)	pedicle cannulation (own AR/VR)	Distance may not be sensitive to detect significant differences between different training groups. Of note, there is a trend that as training level increases, distance to target decreases.
Abhari et al., 2015[21]	21* (3A, 1F, 3R, 14 graduate student nonclinicians)	brain tumor resection (own AR/VR)	
Cagiltay et al., 2017[22]	53* (13 experienced, 40 beginners)	pituitary endoneurosurgery (own VR)	
Teodoro-Vite et al., 2020[23]	12 (6A, 6R)	aneurysm repair (own VR)	
Roitberg et al., 2013[24]	46* (46M)	pedicle cannulation (own VR)	
Roitberg et al., 2015[25]	77 (4R, 73M)	pedicle cannulation (own VR)	
Hooten et al., 2014[26]	263 (263R)	ventriculostomy (own VR)	
Heredia-Pérez et al., 2019[27]	16 (5A, 11R)	transsphenoidal brain tumor resection (own VR)	
Mirchi et al., 2020[28]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	Post-residents, compared to senior and junior residents, had higher total tip path lengths with the scalpel while touching the disc annulus. This general metric of distance travelled while touching an anatomical structure was selected as one of the final 13 metrics for an artificial neural network (83.3% testing accuracy) to predict a participant's training level.
Ledwos et al., 2020[29]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	

Supplemental Table 1. Studies that utilize distance APMs (n=29). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student. *: When multple tasks were involved in the study, the highest number of participants for any given task, provided that at least 1 clinician was involved, was the number inputted. †: F/R refers to participants who are either fellows or residents. Relative numbers of the 2 are unknown.

Supplemental Table 2

Author, Year	**Participants**	**Procedure (System)**	**Salient Point(s)**
Yudkowsky et al., 2013[8]	16 (16R)	ventriculostomy (ImmersiveTouch)	Time as an APM can refer to both task time and time of resource use with the former being negatively associated with training level. Repetitions of task reduce task time and time needed for fluoroscopy exposure.
Schirmer et al., 2013[3]	14 (14 F/R†)	ventriculostomy (ImmersiveTouch)	
Luciano et al., 2013[7]	63 (63F/R†)	percutaneous spinal needle placement (ImmersiveTouch)	
Bajunaid et al., 2017[9]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	Task time to complete a task may bear little clinical relevance; thus, more advanced metrics that utilize time are necessary. The amount of brain tumor resection divided by time and duration of excess force exemplify the intersection of time with other APM categories, and each has varying success in their ability to differentiate between training level categories.
Azarnoush et al., 2015[10]	2 (1A, 1R)	brain tumor resection (NeuroTouch)	
Winkler-Schwartz et al., 2016[11]	16 (16M)	brain tumor resection (NeuroTouch)	
Gélinas-Phaneuf et al., 2014[12]	72 (62R, 10M)	brain tumor resection (NeuroTouch)	
Holloway et al., 2015[30]	83 (12R, 71M)	brain tumor resection (NeuroTouch)	
Sawaya et al., 2018[31]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	
Siyar et al., 2020[14]	115 (16A, 15R, 84M)	brain tumor resection (NeuroTouch)	
Micko et al., 2017[32]	20 (10R, 10M)	aneurysm exposure (NeuroTouch)	
Bugdadi et al., 2019[15]	6 (6A)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[17]	16 (16M)	brain tumor resection (NeuroVR)	
Bissonnette et al., 2019[19]	41 (41R)	hemilaminectomy (NeuroVR)	
Mirchi et al., 2020[18]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Abhari et al., 2015[21]	21* (3A, 1F, 3R, 14 graduate student nonclinicians)	brain tumor resection (own AR/VR)	Whereas one study championed a slower time of task completion as an indication of safety with a new position-based dynamics system, another developed their own scoring methodology with faster times equating to better performance. Time measurements by themselves may not be useful across the wide breadth of VR systems, procedures, and interventions for these studies.
Heredia-Pérez et al., 2019[27]	16 (5A, 11R)	transsphenoidal brain tumor resection (own VR)	
Teodoro-Vite et al., 2020[23]	12 (6A, 6R)	aneurysm repair (own VR)	
Hooten et al., 2014[26]	263 (263R)	ventriculostomy (own VR)	
Cagiltay et al., 2017[22]	53* (13 experienced, 40 beginners)	pituitary endoneurosurgery (own VR)	
Roitberg et al., 2013[24]	46* (46M)	pedicle cannulation (own VR)	
Roitberg et al., 2015[25]	77 (4R, 73M)	pedicle cannulation (own VR)	
Mirchi et al., 2020[28]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	Post-residents, compared to junior residents, had higher disc annulus contact time with the scalpel and lower burr contact time. The contact time of left vertebral artery was one of the final 13 metrics (out of 369) chosen for the artificial neural network (83.3% testing accuracy) to predict a participant's training level.
Ledwos et al., 2020[29]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	

Supplemental Table 2. Studies that utilize time APMs (n=25). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student. *: When multple tasks were involved in the study, the highest number of participants for any given task, provided that at least 1 clinician was involved, was the number inputted. †: F/R refers to participants who are either fellows or residents. Relative numbers of the 2 are unknown.

Supplemental Table 3

Author	**Participants**	**Procedure (System)**	**Salient Point(s)**
Mirchi et al., 2020[28]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	Artificial neural networks classified 3 groups of participants (post-residents, senior residents, and junior residents) with 13 metrics spanning 4 categories, one of which is motion with metrics including linear velocity, angular velocity, and acceleration.
Winkler-Schwartz, et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	In all machine learning algorithms, some form of single or bimanual movement was included in their final list of performance metrics, such as jerk of instrument, velocity of instrument, diverging of instrument tips, rate of slowing down of instrument, and change in tip distance.
Heredia-Pérez et al., 2019[27]	16 (5A, 11R)	transsphenoidal brain tumor resection (own VR)	Kinematic performances, namely velocity, acceleration, and jerk, were measured for dynamic and constant motion scaling. Dynamic motion scaling has allowed for finer movements (represented by lower kinetic metrics) in sensitive operative areas.
Bissonnette et al., 2019[19]	41 (41R)	hemilaminectomy (NeuroVR)	The support vector machine algorithm achieved an accuracy of 97.6% using 12 metrics, 8 of which describe motion of the tools with 5 involving velocity or acceleration of an instrument
Siyar et al., 2020[14]	115 (16A, 15R, 84M)	brain tumor resection (NeuroTouch)	Tremors, which utilized the motion of the instrument tip in the x, y, and z coordinate system, were lower in the skilled group (practicing neurosurgeons and senior residents) than the novice group (junior residents and medical students).
Teodoro-Vite et al., 2020[23]	12 (6A, 6R)	aneurysm repair (own VR)	While kinematic measures could not differentiate between residents and staff neurosurgeons, the aneurysm clipping task with versus without exploration of the Sylvian fissure demonstrated significant differences in velocity, acceleration, and jerk with higher values in the former task.
Mirchi et al., 2020[18]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	With an accuracy of 92%, the virtual operative assistance used mean acceleration of bipolar, a metric reflecting movement, as one of the final 4 selected metrics to bin participants into skilled (staff neurosurgeons, neurosurgery fellows, senior residents) and novice (junior residents, medical students) groups.

Supplemental Table 3. Studies that utilize kinematic APMs (n=7). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student.

Supplemental Table 4

Author	**Participants**	**Procedure (System)**	**Salient Point(s)**
Gélinas-Phaneuf et al., 2014[12]	72 (62R, 10M)	brain tumor resection (NeuroTouch)	A wide variety of force APMs have been recently developed, such as force pyramids and force histograms, along with traditional metrics, such as maximum force applied and sum of forces with an instrument. These metrics reflect operator safety, and in large, more skilled participants apply lower forces.
Bajunaid et al., 2017[9]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	
Azarnoush et al., 2015[10]	2 (1A, 1R)	brain tumor resection (NeuroTouch)	
Winkler-Schwartz et al., 2016[11]	16 (16M)	brain tumor resection (NeuroTouch)	
Micko et al., 2017[32]	20 (10R, 10M)	aneurysm exposure (NeuroTouch)	
Sawaya et al., 2018[31]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	
AlZhrani et al., 2015[13]	33 (17A, 16R)	brain tumor resection (NeuroTouch)	
Azarnoush et al., 2017[33]	115 (16A, 15R, 84M)	brain tumor resection (NeuroTouch)	
Holloway et al., 2015[30]	83 (12R, 71M)	brain tumor resection (NeuroTouch)	
Bugdadi et al., 2019[15]	6 (6A)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Winkler-Schwartz et al., 2019[17]	16 (16M)	brain tumor resection (NeuroVR)	
Mirchi et al., 2020[18]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	
Bissonnette et al., 2019[19]	41 (41R)	hemilaminectomy (NeuroVR)	
Teodoro-Vite et al., 2020[23]	12 (6A, 6R)	aneurysm repair (own VR)	(Max) forces applied during various lobes and an artery in an aneurysm repair task could not distinguish between residents and neurosurgeons. When considering force applied, however, several studies found it was important to assess haptic perception. Performance on tasks relevant to motor planning, spatial memory, and haptic perception were combined into a sensory-motor quotient. Residents had higher scores on this quotient compared to neurosurgery residency applicants.
Roitberg et al., 2015[25]	77 (4R, 73M)	pedicle cannulation (own VR)	
Roitberg et al., 2013[24]	46* (46M)	pedicle cannulation (own VR)	
Mirchi et al., 2020[28]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	While duration of excess force may not be successful in differentiating training levels, the maximum amount of force applied to different anatomic structures make up 3 of the final 13 APMs (out of 369 metrics) chosen for an artificial neural network (83.3% testing accuracy) to predict a participant's training level.
Ledwos et al., 2020[29]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	

Supplemental Table 4. Studies that utilize force APMs (n=19). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student. *: When multple tasks were involved in the study, the highest number of participants for any given task, provided that at least 1 clinician was involved, was the number inputted.

Supplemental Table 5

Author	Participants	Procedure (System)	Salient Point(s)
Bajunaid et al., 2017[9]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	Blood loss served as both an intentional stressor in a brain resection stress scenario and a performance metric for brain resections thereafter. A statistically significant improvement in blood loss before and after the stress scenario was observed for the neurosurgeon and senior resident groups, not for the junior resident and medical student groups.
Bugdadi et al., 2019[15]	6 (6A)	brain tumor resection (NeuroVR)	For the expert neurosurgeons, there was no significant difference in the performance metric of blood loss between the Omni and Entact haptic devices throughout the practice sessions.
Winkler-Schwartz et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	In discriminant analysis and support vector algorithms, some form of blood loss was included in their final list of 8 performance metrics each, such as change in blood in view, bleeding speed, and change in bleed speed.
Winkler-Schwartz et al., 2016[11]	16 (16M)	brain tumor resection (NeuroTouch)	Peer surgeons have blindly rated participants on a sliding ordinal scale, and top-rated participants had lower blood loss for a brain tumor resection task than either middle or low-rated participants.
Winkler-Schwartz et al., 2019[17]	16 (16M)	brain tumor resection (NeuroVR)	While there was a significant negative correlation between visually assessed hemostasis and blood loss in a simulated brain tumor resection task, hemostasis has the highest number of visual rating scale subcomponents that are correlated with various APMs like distance, force, and volume. Hemostasis cannot by itself fully predict blood loss and vice versa.
Mirchi et al., 2020[18]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	With an accuracy of 92%, the virtual operative assistance used rate of bleeding, a metric reflecting safety, as one of the final 4 selected metrics to bin participants into skilled (neurosurgeons, neurosurgery fellows, senior residents) and novice (junior residents, medical students) groups.

Supplemental Table 5. Studies that utilize blood loss APMs (n=6). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student.

Supplemental Table 6

Author, Year	Participants	Procedure (System)	Salient Point(s)
Bajunaid et al., 2017[9]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	At baseline, neurosurgeons had statistically higher tumor percentage resection than the other participants groups and brain volume removed compared to medical students. During the stress scenario in which a VR brain tumor underwent uncontrollable bleeding, junior residents and medical students had significantly lower tumor resection percentage and brain volume removed.
Azarnoush et al., 2015[10]	2 (1A, 1R)	brain tumor resection (NeuroTouch)	In the present pilot study, a neurosurgeon was able to achieve a lower volume of normal brain resection, which reflects operator safety, compared to a resident without sacrificing a reduced percentage of tumor resection.
Winkler-Schwartz et al., 2016[11]	16 (16M)	brain tumor resection (NeuroTouch)	Peer surgeons have blindly rated participants on a sliding ordinal scale. Top-rated participants had statistically higher tumor percentage removed than either middle or low-rated participants while having statistically lower brain volume removed than low-rated participants.
Gélinas-Phaneuf et al., 2014[12]	72 (62R, 10M)	brain tumor resection (NeuroTouch)	Senior residents, compared to junior residents and medical students, had a statistically significant higher percentage of tumor removed, but not normal brain volume.
Bugdadi et al., 2019[15]	6 (6A)	brain tumor resection (NeuroVR)	Expert neurosurgeons had no significant differences between the Omni and Entact haptic systems in either tumor percentage resection or brain volume resected across the 5 practice sessions.
Winkler-Schwartz et al., 2019[16]	50 (14A, 4F, 20R, 12M)	brain tumor resection (NeuroVR)	In naive Bayes (85% accuracy), support vector (76% accuracy), and discriminant analysis (78% accuracy) algorithms, change in volume of tumor was included in the final list of 9 metrics for the naive Bayes algorithm and final list of 8 metrics for both the support vector and discriminant analysis algorithms.
Winkler-Schwartz et al., 2019[17]	16 (16M)	brain tumor resection (NeuroVR)	Tumor percentage resection, a metric for quality of performance, was positively correlated with hemostasis, instrument handing, economy of movement, overall flow, and overall score, which are 5 of the 7 elements in the Objective Structured Assessment of Technical Skills (OSATS). Brain volume, a metric for operator safety, was positively correlated with only hemostasis. All the aforementioned correlations are statistically significant.
Bissonnette et al., 2019[19]	41 (41R)	hemilaminectomy (NeuroVR)	Two spine surgeons selected 36 metrics for the support vector machine algorithm (97.6% accuracy) of which two are volume of resections APMs (volume of ligamentum flavum and volume removed while simultaneously using the suction and the burr). Of the final 12 metrics selected by the algorithm, none had included a volume of resection APM.
AlZhrani et al., 2015[13]	33 (17A, 16R)	brain tumor resection (NeuroTouch)	Whereas neurosurgeons had a lower tumor percentage removal and normal brain volume removed, senior and junior residents experienced the opposite with higher values. This may support the fact that neurosurgeons most value safety during brain tumor resection.
Holloway et al., 2015[30]	83 (12R, 71M)	brain tumor resection (NeuroTouch)	Residents removed similar amounts of tumor volume in all sessions, while medical students significantly removed more tumor volume and normal brain volume in the 4th session compared to the 1st. Despite the trend, medical students and residents did not demonstrate statistically significant differences for these APMs, but residents did have significantly higher tumor removal effectiveness (the percentage of tumor removed divided by the percentage of healthy brain removed).
Sawaya et al., 2018[31]	24 (6A, 12R, 6M)	brain tumor resection (NeuroTouch)	Significant differences were found between the different quadrants of brain tumor resection, which represent hand ergonomic conditions. There seems to be a progressive specialization to specific quadrants as training level increases, as measured by mean tumor volume removed per second on mean force applied per second. (i.e. while medical students do not adapt their performance by the quadrant, neurosurgeons demonstrate a strong favorability of one relative to another).
Mirchi et al., 2020[28]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	Artificial neural networks classified 3 groups of participants with 13 metrics spanning 4 categories. Volume of resection APMs represent safety through the metric of voxels removed from an anatomical structure, and efficiency through the frequency of volume or an anatomic structure removal with an instrument.
Ledwos et al., 2020[29]	21 (4A, 5F, 12R)	anterior cervical discectomy and fusion (Sim-Ortho)	Post-residents, compared to junior residents, removed more disc nucleus with the scalpel but less C5 with the burr. Both reached statistical significance.

Supplemental Table 6. Studies that utilize volume of resection APMs (n=13). For each, last name of first author, year of publication, number of participants (further subdivided by training level), procedure type, procedure system, and summaries are listed. The following key was used for the subdivision of participants: A = attending, F = fellow, R = resident, M = medical student.

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