INR INTERVENTIONAL NEURORADIOLOGY

Interventional Neuroradiology
1–5

DOI: 10.1177/15910199241304851
journals.sagepub.com/home/ine
Sage

Haptic feedback in robotic endovascular neurosurgical intervention: A necessity or a commodity?

Gilbert Gravino

Abstract

Traditionally, both visual and haptic feedback have been regarded as elementary aspects of endovascular neurosurgical intervention. The literature acknowledges that the lack of haptic feedback and the reliance on visual feedback alone in robotic endovascular neurosurgical intervention (RENI) is a limitation. However, several operators who are at the forefront of applying this technology appear to have become quickly accustomed to visual feedback alone. Some have explained their initial scepticism, but upon using the technology they eventually saw the lack of haptic feedback as less of an obstacle and started to regard visual feedback alone as a feasible and safe means to perform procedures. Therefore, this begs the question as to whether haptic feedback is in effect a necessity or a commodity. In this commentary, several considerations are made, presenting arguments supporting the idea that haptic feedback may not be an absolute necessity, and their potential counterarguments. Such reflection and discussion on the topic of haptic feedback in RENI is timely and presently warranted to guide its research and development.

Keywords

Stroke, aneurysm, neuroradiology, technology, robotics

Received 30 October 2024; accepted: 13 November 2024

Traditionally, both visual and haptic feedback have been regarded as elementary aspects of endovascular neurosurgical intervention (ENI). While visual feedback largely facilitates the procedures, haptic feedback is well known to improve operator performance by increasing situational awareness beyond that provided by 2D or 3D imaging.[1,2] Visual feedback provides real-time observation of device movements, behaviours, and interactions as they are navigated through and manipulated within the vasculature. With experience, operators are even able to use visual cues to infer and estimate the force and tension being applied on the devices and respective anatomy. On the other hand, haptic (aka tactile) feedback involves friction, viscous, and impact forces transmitted to the fingertips of the operator. This provides a more tangible understanding of the forces and tensions at play in the operating system of wires, catheters, and devices interacting with the patient's anatomy. The industry that develops new devices for such operations has been addressing both aspects, instructing operators on what to expect to visualise on the high-resolution angiography suite screens and the subtle tactile sensations they ought to feel as they use and manipulate a device. Experienced endovascular neurosurgical interventionalists (ENIs) mentoring their fellows also instruct and train them in both these valued elementary skills, which take time and a lot of practice to master and appreciate in their entirety.

The literature on the currently available robotic endovascular neurosurgical intervention (RENI) methods acknowledges that the lack of haptic feedback and the reliance on visual feedback alone is a limitation. However, several operators who are at the forefront of applying this technology – and have done so on a small series of patients – appear to have become somewhat accustomed to visual feedback alone.[3–5] Some have explained their initial scepticism, but upon using the technology they eventually saw the lack of haptic feedback as less of an obstacle and felt that visual feedback alone can be feasible and safe to perform procedures. This includes specialists from both neurosurgical and neuroradiology training backgrounds. Therefore, this begs the question as to whether haptic feedback is in effect a necessity or a commodity (i.e. a replaceable aspect in the skill set of ENIs).

Consultant Neuroradiologist (Interventional and Diagnostics), The Walton Centre NHS Foundation Trust, Liverpool, UK

Corresponding author:
Gilbert Gravino, Consultant Neuroradiologist (Interventional and Diagnostics), The Walton Centre NHS Foundation Trust, Liverpool, UK.
Email: gilbert.gravino@nhs.net

Does visual feedback alone by an experienced operator sufficiently compensate for the lack of haptic feedback experienced with current robotic systems?

As operators of ENI, we are already accustomed to treating disease in the brain and spine using the remote means of peripheral vascular access. The idea of taking this to a different level with remote operations that can mitigate our geographical limitations is alluring. Perhaps even more appealing is the possibility of mitigating time delays when working against the clock to deliver a time-sensitive procedure like thrombectomy as quickly as possible to a patient who is suffering an acute ischaemic stroke in a remote part of the country. RENI has been performed in live patients and reported for other types of procedures, including aneurysm coiling (with and without stent assistance), Woven-EndoBridge deployment, and flow diverter deployment.[3,6] At present, there are no reported cases of telerobotic thrombectomy for a live stroke patient, although this has been reported on a simulated patient.[7] It is important to be conscious of the fact that such an attractive and futuristic concept poses the risk of overlooking or understating the need for some aspects of ENI, which have thus far been considered elementary but currently remain a challenge. Therefore, this commentary merely poses the question as to whether this could be the case with haptic feedback in the context of RENI. There are several arguments supporting and countering the idea that haptic feedback is not an absolute necessity. This commentary presents several considerations on this topic.

Considerations on operator experience and technical aspects of the procedure

It is argued that while highly experienced ENIs can get comfortable quickly with visual feedback alone and can do so without haptic feedback after a short learning curve, fellows and junior ENIs will need a longer learning curve to gain such competence. The counterargument is that no matter how experienced the ENIs, haptic feedback remains a must. Using the Swiss cheese model of risk analysis as an analogy (Figure 1), this view holds that visual and haptic feedback are two separate and important layers of safety, among several other layers. Therefore, irrespective of how experienced or not the ENIs are, why would they give up the safety net provided by haptic feedback? Importantly, the Swiss cheese model may not fully capture the nuanced interplay between haptic feedback and visual feedback, since current robotic systems give operators the potential to develop a heightened awareness of visual feedback.

ENIs with an abundance of experience have mentored and trained fellows and junior colleagues, and even proctored other equally experienced colleagues. Such tasks already demand a very sharp eye for visual cues to then direct and advise the hands-on operator who is training or learning an unfamiliar procedure. However, a trainee who is unsure about the haptic feedback they are sensing or is suspicious of an impending complication can easily hand over to their mentor/proctor, who can either provide reassurance or confirm the suspicion. The quick and ease of access to haptic feedback afforded by a mentor/proctor instructing a conventional ENI procedure is not possible with RENI.

Some may argue that ENIs base more of their decisions on visual rather than haptic feedback. While this could be the case in many situations, there are numerous other situations when this may not be so. For the former to hold true, one would have to assume that, invariably, visual feedback is as immediate and instantaneous or even precedes haptic feedback. However, it is also very plausible that haptic feedback could precede visual feedback, prompting the ENIs to change tact or decide differently in the way they proceed to ensure safety and avoid complications.

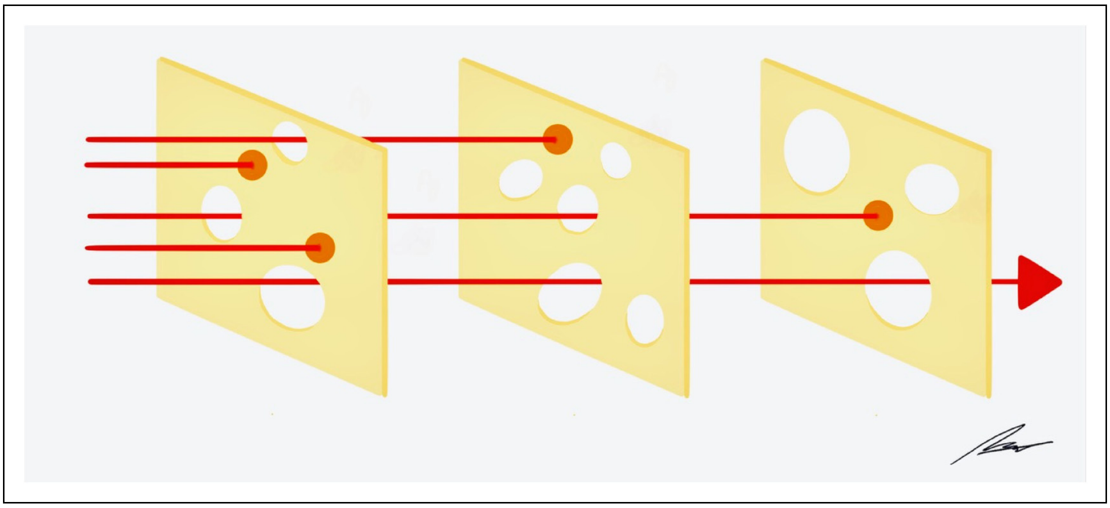

Figure 1. The Swiss cheese model of accident causation illustrates that, although many layers of defence lie between hazards and accidents, there are flaws in each layer that, if aligned, can allow the accident to occur. In this diagram, four hazard vectors are stopped by the defences, but one passes through where the 'holes' are lined up *(Illustration by Dr David Gendy).*

Consider a simple scenario where a wire or a catheter tip is being pushed against a vessel wall. Enough force, which can be haptically appreciable with direct manual manipulation (conventional operations) but not with robotics, would have to be applied on the tip before it deforms and provides the visual feedback necessary to indicate that there is too much friction. At that point, it may be too late, and a vessel wall dissection or perforation may have already been caused. In this case, the preceding haptic feedback could alert the operator earlier, indicating that further advancement of the device may result in damage of the vessel wall, thereby prompting them to adopt a different manoeuvre and avoid dissection altogether. However, current systems do incorporate alerting technology such as the ‘slip sign’. This gets triggered when there are unintended movements or slippage of a device or the robotic drive mechanism, either from increased resistance or friction, improper device engagement, or mechanical issues with the system itself. Therefore, the operator gets notified to indicate a discrepancy between the commanded movement and the actual movement of the device.

In conventional practice, there are many subtle tactile sensations that inform the ENIs on how to proceed, including the sensory feedback required to adjust force with which to inject contrast for optimal opacification, choosing the size of the next coil based on resistance gauged from pushing the last coil into an aneurysm, or appreciating device behaviour caused by damage, kinking, or destabilisation of the coaxial system due to tortuous and ectatic anatomy (e.g. a guide catheter outside the field of view receding back). In some cases, it may be the evaluation of visual and haptic feedback together that gives enough information to raise consideration of a possible complication. Consider another scenario with a thin-flap vessel wall dissection which may be too subtle to cause odd device behaviour and to raise suspicion based on visual feedback alone, but combined with the haptic feedback prompts the operator to pause and check with an angiographic run. There are yet other manoeuvres which are not necessarily coupled with visual feedback and therefore may remain completely unappreciated in the absence of haptic feedback, such as the clamping sensation when re-sheathing the proximal spiral section of some stroke stent-retrievers, the initial give after un-sheathing a short distal segment of a stent, or when starting re-sheathing of a device after which the manoeuvre requires less force.

Additionally, the use of a robotic arm may be regarded as an added layer of complexity, because in the absence of one-to-one visual feedback (i.e. an applied forward force at the proximal end of the device outside the patient not translating into a proportional forward motion on fluoroscopy), the operator cannot be sure whether this is due to anatomical and/or device limitations or due to a possible fault in the robotic arm. Conversely, an operator handling and pushing the device directly with their fingers remains aware of the degree of force that they are applying, and if they notice a lack of one-to-one feedback they know immediately that the problem is to do with difficult anatomy and/or device limitations and/or complications.

Considerations on already existing experience

The cases of RENI that have been performed and reported so far demonstrate a good success rate and safety profile, which is testament to the effectiveness of robotics in this field.[3,6] However, the relatively small case series published so far are prone to selection bias, since, understandably, the operators would have likely been inclined to be highly selective in their first robotic cases, favouring patients with anatomy and pathology that are towards the lower end of the complexity spectrum. The lack of haptic feedback in RENI could be of greater concern when dealing with more complex cases where the risk of complications and the technical challenges are much higher.

Robotic surgery is being widely utilised in other specialities, encompassing urology, gynaecology, general surgery, cardiac, bariatric, head and neck, and paediatric surgery. The technology used to perform these procedures also lacks haptic feedback, and yet they are proving to have a high safety profile.[8,9] These positive results are being achieved despite such robotic surgeries having the extra hurdle of surgeons needing to become accustomed to digital visualisation of the operative field (as opposed to direct visualisation). This includes becoming accustomed to enhanced magnification, depth perception, spatial awareness, and hand-eye coordination. In this regard, RENI operators have the advantage of retaining the same mode of visualisation which they have already been accustomed to for many years, involving fluoroscopy with attention to fine, delicate details and movements.

The main caveat lies in the fact that ENIs deal with neurovascular anatomy that is as delicate as it gets, arguably more so than many other organ systems. It tends to be unforgiving, with critical brain function at stake and potentially devastating outcomes. Even among vascular procedures, ENI is arguably the riskiest. The wall of a cerebral artery is 150–300 μm thick with just 3–6 layers of smooth muscles in the tunica media and little external support, whereas a systemic artery has a wall thickness of 500–2000 μm with 30–40 layers of smooth muscles in the tunica media and better external support from surrounding loose connective tissue.[10–13] In the case of a cerebral aneurysm, the tunica media is either partially or completely absent and the wall thickness may be as thin as 20 μm.[11] Therefore, this must also be taken into consideration when developing RENI.

Discussion

The currently available robotic platforms do not provide haptic feedback. The development of such a system which is effective requires a measure of forces on the guide wire, catheter and devices, and a mechanism for the operator to appreciate these forces within the control unit. Researchers have already experimented with force sensors in catheter tips, sensing mechanisms in responder systems, mathematical modelling, and image-based haptic feedback.[14–19] Some of these techniques can estimate forces accurately, but an even bigger challenge relates to accurately translating these into a realistic representation of forces transmitted to the operator in the control unit. Stylus ('joystick') controllers do not replicate the forces felt by an operator when directly handling and manipulating the devices.[20,21] To address this issue, researchers developed a controller system with haptic feedback which tangibly replicates the devices normally present at the operating table, allowing the operator to control the robot with movements equivalent to the manual procedure, i.e. applying conventional axial and radial motion to an input catheter in the control unit. This system produced catheter movements that were within 1 mm of linear motion and 1 degree of rotation, and its haptic feedback properties reduced the amount of force applied to an aortic wall phantom when compared to manual manipulation.[22,23] Haptic syringe devices have also been incorporated into angiographic simulators to mimic the sensory feedback during administration of contrast, but are not yet a feature in robotic systems.[24]

Future robotic systems could potentially include a haptic interface, gathering data from cumulative experiences, and using machine learning to integrate force measurement systems, force warning systems, and super-human reaction times through motion feedback loops.[25,26] Such technology could be used to determine the degree of traction that can be applied to a microcatheter without rupturing the vessel, or to retract a microwire in time to avoid an aneurysm perforation if the microcatheter jumps.[27] Therefore, haptic interface coupled with artificial intelligence may provide a means to maintain or potentially improve upon the safety profile of conventional ENI procedures.

ENI training involves a learning curve, with trainees starting off being initially unable to appreciate subtle haptic feedback. Over time, and with a lot of practice, such a skill can be nurtured and perfected. After a lot of effort and dedication to develop this skill along with many others demanded of such a speciality, many take pride in their ability to effectively interpret haptic feedback and apply this in their practice to anticipate and avoid procedural difficulties and complications. This may be particularly so for more junior ENIs who are fond of their more recently acquired haptic skills and perhaps less proficient at picking on visual cues compared to highly experienced ENIs with many years of practice under their belt. Therefore, one may expect junior ENIs to have a greater inclination towards haptic feedback being developed for RENI.

Conclusion

The challenge of developing haptic feedback as an integral part of RENI should not unneccesarily hinder or delay the application of this technology. It remains debatable whether haptic feedback is a necessity, and it may be argued that in certain circumstances RENI without haptic feedback is still better than no procedure at all - such as remote robotic thrombectomy for patients who live remotely and would otherwise not be able to access and benefit from this procedure. However, without ENIs emphasising the need for haptic feedback to be developed, there is the risk that the industry neglects this challenge and misses a window of opportunity while the technology of RENI is at its infancy and still being developed. Therefore, further reflection and discussion on the topic of haptic feedback in RENI is timely and warranted in order to guide its research and development.

Declaration of conflicting interests

The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Author has an unrestricted fund from WallabyPhenox and a grant from Medtronic for separate research.

Funding

The author received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Gilbert Gravino https://orcid.org/0000-0003-2894-7098

References

1. Zamorano L, Li Q, Jain S, et al. Robotics in neurosurgery: state of the art and future technological challenges. *Int J Med Robot* 2004; 1: 7–22.
2. van der Meijden OA and Schijven MP. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surg Endosc* 2009; 23: 1180–1190.
3. Mendes Pereira V, Rice H, De Villiers L, et al. Evaluation of effectiveness and safety of the CorPath GRX robotic system in endovascular embolization procedures of cerebral aneurysms. *J Neurointerv Surg* 2024; 16: 405–411.
4. LINCC. How do robotic procedures work in real life? Available from https://www.linnc.com/LINNC-TV/Clinical-videos/Interview-of-Prof.-Vitor-Mendes-Pereira-at-LINNC-Paris-2021
5. ESNR. 47th ESNR Annual Meeting – Robotics and AI in Neurointervention: Current and Future Role. Attended on 19th September 2024.
6. Łajczak PM, Jurek B, Jóźwik K, et al. Bridging the gap: robotic applications in cerebral aneurysms neurointerventions–a systematic review. *Neurosurg Rev* 2024; 47: 150.
7. NeuroNews. XCath successfully performs first public telerobotic mechanical thrombectomy demonstration. 2024. Available from https://neuronewsinternational.com/xcath-successfully-performs-first-public-telerobotic-mechanical-thrombectomy-demonstration/
8. Chatterjee S, Das S, Ganguly K, et al. Advancements in robotic surgery: innovations, challenges and future prospects. *J Robot Surg* 2024; 18: 28.
9. Sheetz KH, Claflin J and Dimick JB. Trends in the adoption of robotic surgery for common surgical procedures. *JAMA Netw Open* 2020; 3: e1918911.
10. Brown WR and Thore CR. Review: cerebral microvascular pathology in aging and neurodegeneration. *Neuropathol Appl Neurobiol* 2011; 37: 56–74.

11. Frosen J, et al. Histological structure of intracranial arteries and its relationship to aneurysm formation. *J Neurosurg* 2015; 122: 941–946.
12. Humphrey JD. Mechanics of the arterial wall: review and directions. *Crit Rev Biomed Eng* 1995; 23: 1–162.
13. Wolinsky H and Glagov S. Comparison of abdominal and thoracic aortic medial structure in mammals. *Circ Res* 1969; 25: 677–686.
14. Wang T, Zhang D and Da L. Remote-controlled vascular interventional surgery robot. *Int J Med Robot* 2010; 6: 194–201.
15. Condino S, Ferrari V, Freschi C, et al. Electromagnetic navigation platform for endovascular surgery: how to develop sensorized catheters and guidewires. *Int J Med Robot* 2012; 8: 300–310.
16. Guo J, Guo S, Shao L, et al. Design and performance evaluation of a novel robotic catheter system for vascular interventional surgery. *Microsyst Technol* 2016; 22: 2167–2176.
17. Zhang L, Guo S, Yu H, et al. Performance evaluation of a strain-gauge force sensor for a haptic robot-assisted catheter operating system. *Microsyst Technol* 2017; 23: 5041–5050.
18. Dagnino G, Liu J and Memk A. Haptic feedback and dynamic active constraints for robot-assisted endovascular catheterization. In: 2018 IEEE/RSJ International Conference on intelligent robots and systems. IROS, Madrid, Spain, 2018: 1770–1775.
19. Eslahpazir BA, Goldstone J, Allemang MT, et al. Principal considerations for the contemporary high-fidelity endovascular simulator design used in training and evaluation. *J Vasc Surg* 2014; 59: 1154–1162.
20. Bao X, Guo S, Xiao N, et al. Compensatory force measurement and multimodal force feedback for remote-controlled vascular interventional robot. *Biomed Microdevices* 2018; 20: 74.
21. Jayender J, Patel RV and Nikumb S. Robot-assisted active catheter insertion: algorithms and experiments. *Int J Robot Res* 2009; 28: 1101–1117.
22. Thakur Y, Bax JS, Holdsworth DW, et al. Design and performance evaluation of a remote catheter navigation system. *IEEE Trans Biomed Eng* 2009; 56: 1901–1908.
23. Payne CJ, Rafii-Tari H and Yang GZ. A force feedback system for endovascular catheterisation. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems. Vilamoura-Algarve, Portugal, 2012: 1298–1304.
24. Huang D, Tang P, Wang X, et al. New haptic syringe device for virtual angiography training. *Comput Graph* 2019; 80: 97–103.
25. Haraguchi K, Miyachi S, Matsubara N, et al. A mechanical coil insertion system for endovascular coil embolization of intracranial aneurysms. *Interv Neuroradiol* 2013; 19: 159–166.
26. Sugiyama T, Lama S and Gan LS. Forces of tool-tissue interaction to assess surgical skill level. *JAMA Surg* 2018; 153: 234–242.
27. Goyal M, Sutherland GR, Lama S, et al. Neurointerventional robotics: challenges and opportunities. *Clin Neuroradiol* 2020; 30: 203–208.