MEKATRONIKA
e-ISSN: 2637-0883
VOL. 3, ISSUE 1, 10 – 17
DOI: https://doi.org/10.15282/mekatronika.v3i1.7073

ORIGINAL ARTICLE

A Study of Haptic Effects in Endovascular Interventions

H.R. Ramli[1*], E. Ako[2], M.I. Saripan[3] and F. Bello[4]

[1]Department of Electrical and Electronics Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
[2]Chelsea & Westminster Hospital,369 Fulham Road, London SW10 9NH, United Kingdom.
[3]Department of Computer and Communications Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
[4]Center for Engagement and Simulation Science, Imperial College London, 3rd Floor Chelsea and Westminster Hospital (Academic Surgery), 369 Fulham Road, London SW10 9NH, United Kingdom.

ABSTRACT – During an endovascular intervention, interventionists rely on their sense of touch to perform the procedures correctly. However, there is a paucity of literature regarding the intricacies of the haptic component of the interventions. The objectives of this study were to capture the types and magnitude of haptic effects during real-life interventions from subject matter experts. The study consisted of an online questionnaire and a force measurement experiment to help determine the force types and magnitude. Participants were interventionists with significant procedural experience. The data recorded from the online questionnaire and the experimental study was analysed using descriptive statistics and hypothesis testing techniques. Participants identified four different types of haptic effects: translational resistance, rotational resistance, bump effect and heart beat pressure effect. The characteristics of each effect, such as factor of occurrence and direction, were established and they were compared against each other. Translational resistance was recognised as the strongest, followed by rotational resistance, bump effect and heart beat pressure. In the force measurement experiment, the forces involved in the generation of translational resistance were found to be in the range 0-0.5 N in healthy vessels, 0.5 – 1.5 N in tortuous/narrowed vessels and 1.5 – 2 N in calcified or occluded vessels. Measurements for the bump effect provided less conclusive results due to its subtle nature, although current findings suggest forces between 0.1 – 0.2 N. Overall, the study was successful in expanding current knowledge of haptic effects in endovascular interventions, highlighting the existence of a variety of effects and their characteristics.

ARTICLE HISTORY
Received: 3rd April 2021
Revised: 12th May 2021
Accepted: 15th June 2021

KEYWORDS
Haptic Feedback
Haptic Effects
Endovascular Force
Endovascular Intervention

INTRODUCTION

During an endovascular intervention, long and flexible instruments (guidewire and catheter) are manipulated in tandem to diagnose and treat diseased vessels. The interactions of the tools with the endoluminal environment at the distal end are detected as resistance sensations at the proximal end by the sense of touch of the operator. We refer to these as 'haptic effects', where the term haptic refers to the multimodal sense of touch and signals that are involved when objects are manipulated by human hands. These haptic effects can be used to determine the instrument's position and the condition of the vasculature being traversed. Thus, they are a valuable tool for decision making, together with the visual information obtained from fluoroscopic imaging. Better understanding and quantification of such effects may also help improve the realism of endovascular intervention simulators.

Though the existence of such haptics effects is recognized [1-3], there is a paucity of studies of the different types of haptic effects and the range of forces involved. Ideally, investigations into this subject matter would be a collaborative effort to establish a validated cognitive task analysis [4,5] and direct in vivo force measurements [6]. However, obtaining the required equipment, ethical consent and such collaboration is very challenging and time-consuming. This has led to the use of theoretical and experimental means to learn more about the forces involved [7-9].

MATERIALS AND METHODS

This paper presents a study to investigate the various types of haptic effects present in endovascular interventions and their characteristics based on Subject Matter Experts (SMEs) feedback. Approval was granted by the Imperial College Research Ethics Committee (ICREC_14_12_9). It consisted of two parts: an online questionnaire and a force range measurement experiment. Participants had at least one year of endovascular intervention training in the Cath Lab or

***CORRESPONDING AUTHOR** |H.R. Ramli | ✉ hrhr@upm.edu.my

performed/assisted in at least 100 endovascular interventional procedures. Recruitment was by e-mail following identification through existing contacts and British Society of Interventional Radiology (BSIR).

Online Questionnaire

Its objective was to elicit the type of haptic effects perceived during endovascular interventions, and their characteristics. Several assumptions were relayed to participants:

- Upon insertion, instruments can experience physical changes due to the increase in environment temperature. It is assumed that these compliance changes are factored into the responses
- Advancing instruments into a ’vessel narrowing’ or ’narrowed vessels’ indicates the instrument is moving into a vessel with a diameter smaller than or close to that of the instrument
- The term ’tortuous vessels’ refers to vessels that are assumed to be inherently tortuous and would maintain its tortuosity as the instruments are passed through it
- The term ’occluded vessels’ refers to vessels that are occluded due to longstanding fibrotic material and not due to recently formed soft thrombus

The questionnaire had two sections: first section gathered participant demographics and second section focused on the different types of haptic effects mentioned by interventionists through informal interviews prior to the study:

i. Translational resistance: A sensation that the movement of the instrument is being restricted or opposed by a force when advancing the instrument
ii. Rotational resistance: A sensation that the movement of the instrument is being restricted or opposed by a force when rotating the instrument
iii. Bump effect: A sudden but subtle jolt of the instrument that occurs when there is a collision between the instrument and branch vessels or pronounced bends
iv. Heart beat pressure effect: A very subtle push felt when the instrument is in proximity to the heart, caused by the pressure of the beating heart displacing a loosely held instrument

There was a total of thirteen primary questions and twenty secondary questions. The questions were designed to investigate the characteristics of each effect using a 5-point Likert scale (Strongly Disagree, Disagree, Neutral, Agree and Strongly Agree). Differences between the haptic effects were also studied using rank-based questions. The questionnaire was administered online with a link to the questionnaire included in the recruitment email.

Force Range Measurement Experiment

The aim was to estimate the range of forces involved in the translational resistance and bump effects since they correspond to the extremes of force strength (translational resistance – stronger force; bump effect – weaker force). Using an experimental setup (Figure 1), the guidewire was first passed through a horizontal guide tube and then into a vertical guide tube allowing the wire to extend downwards. For the resistance effect, a known force F_w was applied in the direction opposite to instrument advancement, F_m, by attaching calibrated weights (50g, 100g, 150g and 200g) to the proximal end of the instrument. As the participants advanced the guidewire, they were asked to relate the level of resistance experienced with that felt when navigating through a specific vessel type, namely: healthy vessel, tortuous vessel, stenosed vessel, vessel with calcified lesions and occluded vessel. The translational resistance test was repeated three times for each weight and three more times without any weights in random order. After each test, participants were asked to record and classify the level of resistance experienced. The procedure was the same for the bump effect experiments, but with lighter weights (5g, 10g and 20g) and participants were asked to concentrate on the initial haptic sensation at the precise moment when resistance is first felt (i.e. the weight is first lifted). This sudden jolt was assumed to resemble the bump effect, with participants asked to rate its strength and realism.

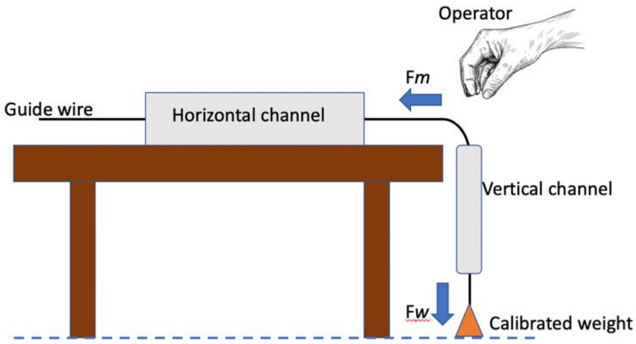

Figure 1. Experimental setup for estimating force of haptic effects

RESULTS: ONLINE QUESTIONNAIRE

Participant Information

A total of 45 participants completed the online questionnaire: 15 (33%) Interventional Cardiologists, 7 (16%) Non Interventional Cardiologists, 18 (40%) Interventional Radiologists and 5 (11%) Vascular Surgeons. In terms of experience, 5 (11%) participants were Junior Registrars, 12 (27%) were Senior Registrars, and 28 (62%) were Consultants. Junior Registrars had 1-3 years of experience (M=2.2, SD=0.84), Senior Registrars 2-8 years of experience (M=4.67, SD=2.15), and Consultants 3-35 years of experience (M=14.64 years, SD=8.87). 15 (33%) participants had trained purely on real patients. 5 (11%) participants on real patients and bench top models, and 9 (20%) on real patients and VR simulators. Only 16 (36%) participants had trained with both bench top models and VR simulators, in addition to real-life training.

Translational Resistance

Figure 2 shows a diverging stacked bar graph of responses regarding translational resistance. Each bar corresponds to a specific question. Positive results are grouped in blue (Strongly Agree and Agree) whereas negative results in red (Strongly Disagree and Disagree) and are distributed right and left of neutral respectively. Bars are thus skewed in the direction of the overall trend. A large majority of the participants (41 – 91.11%) agreed / strongly agreed that a resistance effect can be felt when advancing the instruments through a narrowed vessel. The remaining 4 (8.89%) participants were neutral. This resistance increases with the degree of narrowing experienced by the vessel, as agreed / strongly agreed by 37 (82.22 %) participants. Only 1 (2.22%) participant disagreed as the remaining 7 (15.56%) responded neutrally. The resistance in occluded vessels stops the instrument from being advanced further, according to 33 (73.33%) participants. 7 (15.56%) disagreed and 5 (11.11%) were neutral. Translational resistance can also occur in tortuous vessels as confirmed by a majority of participants (43 – 95.55%) and the strength of the resistance increases with the degree of vessel tortuosity as supported by 41 (91.11%) participants.

30 (66.66%) participants agreed/strongly agreed that no resistance is felt when advancing instruments through a healthy, non-tortuous vessel. 11 (24.44%) participants disagreed with the statement and 4 (8.89%) were neutral. A majority of participants (37 – 82.22%) agreed/strongly agreed that the standard practice is to immediately stop advancing the instruments once an unexpected resistance is felt. 2 (4.44 %) participants disagreed and 6 (13.33%) were undecided. Following the previous question, 21 (46.67%) participants strongly agreed that the next step is to obtain a fluoroscopic image to examine the cause of the detected resistance, with 18 (40%) agreeing, 1 (2.22%) disagreeing and 5 (11.11%) responding neutrally.

In terms of resistance direction, 26 (57.78%) participants agreed / strongly agreed that resistance in narrowed vessels is only felt in one direction, i.e. towards the point of stenosis or narrowing. 16 (35.56%) participants responded neutrally to this statement, whereas 3 (6.67%) disagreed. Once the instrument has passed through the narrowing (stenosis), 21 (46.67%) participants claim that the resistance effect is bidirectional (felt both when advancing and withdrawing the instrument). 22 (48.89%) chose a neutral response and 2 (4.44%) disagreed. In the case of tortuous vessels, the resistance effect was judged to be present for both instrument advancement and withdrawal, according to 23 (51.11%) participants. 19 (42.22%) participants responded neutrally, while 3 (6.67%) disagreed.

Participants were asked to rank the strength of translational resistance felt in different types of vessels using a 1-5 scale system (1 - highest resistance; 5 – least resistance). Participants ranked healthy vessels to have the least resistance (M=4.47,SD=1.375). The resistance was deemed to be more substantial in tortuous vessels (M=3.4,SD=0.836) and increase slightly in vessels with stenosis (M=3.04,SD=0.673). It was then judged to grow stronger in vessels with calcified lesions (M=2.49,SD=0.869) and be at a maximum in occluded vessels (M=1.578,SD=1.322).

Rotational Resistance

Figure 3 shows the rotational resistance questionnaire responses. 22 (48.89%) participants agreed and 17 (37.78%) strongly agreed that there is a resistance felt when rotating instruments within tortuous vessels, while the remaining 6 (13.33%) responded neutrally. Furthermore, 29 (64.44%) participants agreed and 9 (20%) strongly agreed that the rotational resistance is caused by torque that is stored within the instrument(s) as it is bent/twisted. From the 7 participants that replied otherwise, 5 (11.11%) were neutral, while only 2 (4.44%) disagreed. 18 (40%) participants disagreed and 6 (13.33%) participants strongly disagreed with the statement that rotational resistance is not noticeable to the operator's touch. 10 (22.22%) participants replied neutrally and only 11 (24.44%) agreed. This would suggest that rotational resistance can be considered to be a noticeable haptic effect.

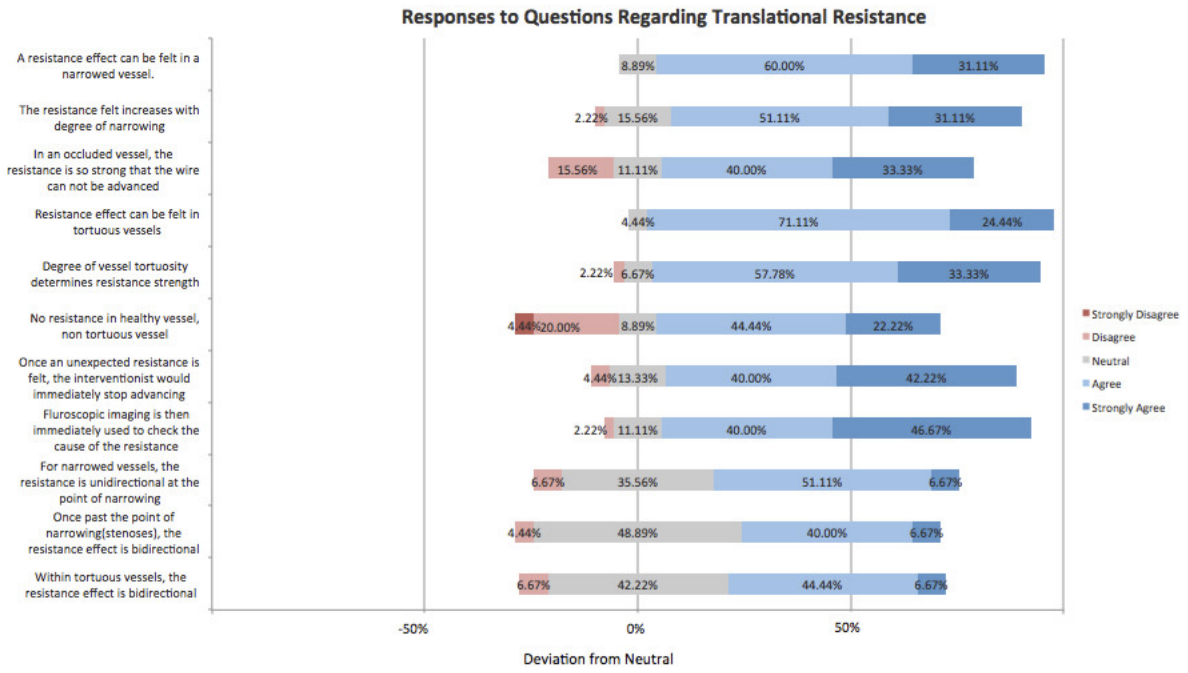

Figure 2. Questionnaire responses regarding translational resistance

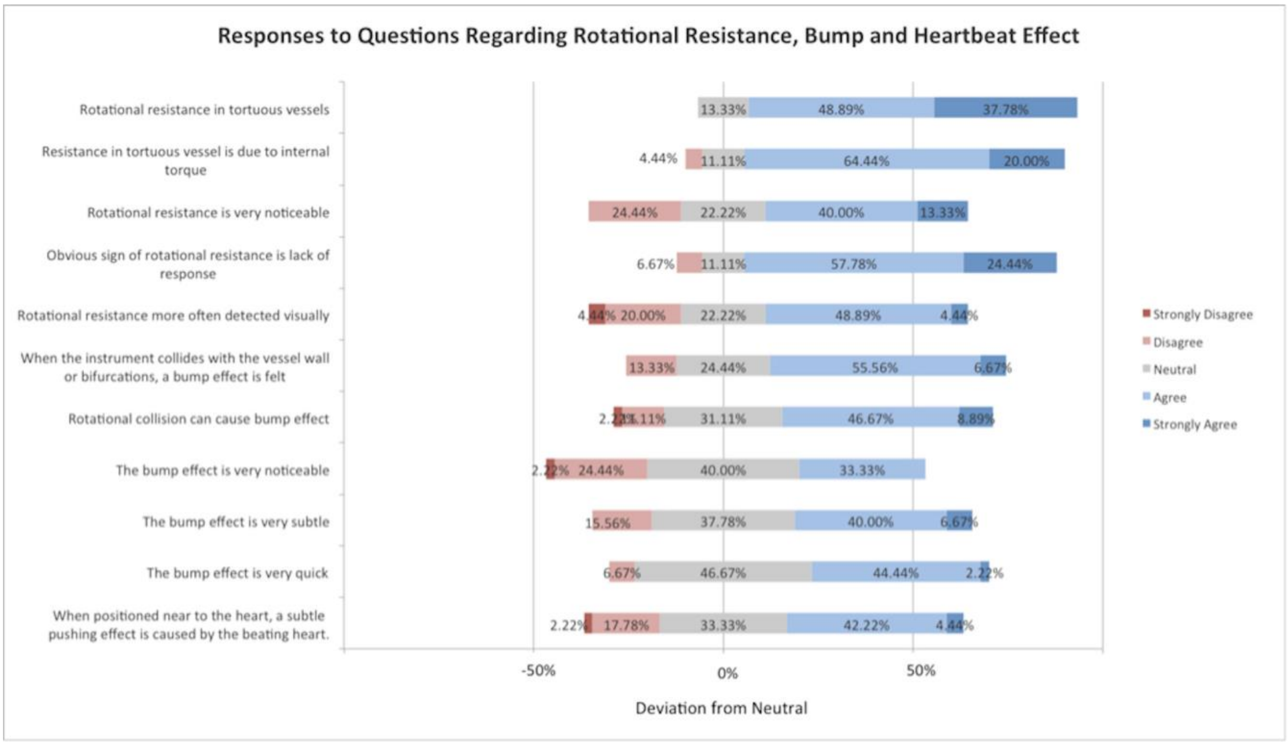

Figure 3 Questionnaire responses regarding rotational resistance, bump and heartbeat effect

Rotational resistance can often be observed through fluoroscopic imaging as it might take several rotations at the proximal end of the instrument to visibly rotate the instrument tip slightly. This statement was agreed by 26 (57.78%) participants and strongly agreed by 11 participants (24.44%). From the remaining 8 participants, 5 (11.11%) responded neutrally and 3 (6.98%) disagreed. Following this, 22 (49%) of the participants agreed and 2 (4.44%) more strongly agreed that the rotational resistance is more often detected visually than through the resulting haptic effect. However, 9 (20%) participants disagreed and 2 (4.44%) participants strongly disagreed with this statement while 10 (22.22%) remained neutral.

Bump Effect & Heartbeat Effect

Responses to the bump effect questions are shown in Figure 3. 25 (55.56%) participants agreed and 3 (6.67%) strongly agreed that a bump effect can be felt on the instruments when they collide with the vessel wall or bifurcations. 6 (13.33%) participants disagreed with the statement, with 11 (24.44%) remaining neutral. According to 25 (55.56%) participants, the same effect can be felt as a result of rotational collisions, but 6 (11.11%) participants disagreed and 14 (31.11%) others are undecided. 15 (33.33%) participants agreed that the bump effect can be described as very noticeable. However, 11 (24.44%) participants disagreed with the statement and 1 (2.22%) strongly disagreed, whereas 18 (40%) participants responded neutrally. The bump effect is said to be very subtle by 18 (40%) participants who agreed and 3 (6.67%) who strongly agreed. However, 7 (15.56%) participants claimed the opposite and disagreed, whereas 17 (37.78%) participants were undecided. Lastly, 20 (44.44%) participants agreed with the claim that the bump effect is very quick, whereas 1 (2.22%) strongly agreed, 3 (6.67%) disagreed and 21 (46.67%) responded neutrally to the statement.

From the gathered responses, 19 (42.22%) participants agreed and 2 (4.44%) strongly agreed that, when the instrument is in proximity to the heart, a subtle pushing effect can be felt that is caused by the pressure of the beating heart. From the 24 remaining participants, 15 (33.33%) were neutral, 8 (17.78%) disagreed and 1 (2.22%) strongly disagreed. The majority of positive responses were expected from interventional/non- interventional cardiologists since their operating region is very close to the heart. However, from the total of 21 participants who agreed or strongly agreed, the majority of these were radiologists and vascular surgeons, (14 (66.67%)) and only 7 (33.33%) were interventional/ non-interventional cardiologists. When asked to rank how noticeable and important each of the different haptic effects is on a scale of 1-4 (1 - most important; 4 - least important), the participants chose Translational Resistance as the most important and noticeable haptic effect (M=1.34). Rotational Resistance was ranked second (M=2.16), followed by the Bump effect (M=2.70) and the Heart Beat Pressure effect (M=3.80) (Figure 3.30). This correlates well with the overall questionnaire findings as there is still some uncertainty in relation to the bump and heart beat pressure effects, whereas the presence of translational and rotational resistance effects is acknowledged by the majority of participants.

RESULTS: FORCE MEASUREMENT EXPERIMENT

Translational Resistance

As shown in Figure 4, 39 (68.42%) responses agree that the 0g weight best represents the resistance felt in healthy vessels. This corresponds with the findings from the questionnaire where 30 (66.67%) participants agreed that no resistance is felt when advancing the guidewire and catheter within a healthy and non-tortuous vessel. Conversely, the weighted average calculated for healthy vessels is 20.18g (Table 1), corresponding to a subtle resistance that coincides with another finding from the questionnaire, where at least 11 (24.44%) participants indicated that there is some resistance felt in the instruments, even when passing through healthy and non-tortuous vessels.

For narrowed vessels or vessels with stenosis, 100g was chosen as the best representation of the resistance on 14 (40%) occasions each. The weighted average is close to that estimate with a value of 97.14g. Similarly, the resistance from the 100 g weight was also selected as the best representation of resistance in tortuous vessels with 17 (42.5%) counts. Thus, according to the weighted average, the resistance in tortuous vessels is slightly stronger than in narrowed vessels (110g vs 97.14g). This differs slightly from the responses of the questionnaire, suggesting that the strength of resistance due to vessel narrowing or stenosis is higher than the resistance due to vessel tortuosity, although there is only a small difference between the two mean response values (3.39 for tortuous vessels and 3.06 for narrowed vessels). However, for vessels with calcified lesions, the 150g weight was the Mode weight, chosen 17 (50%) times and the weighted average value is 155.88g. Lastly, the resistance in occluded vessels, which is expected to be the strongest, was most frequently associated with the 200g weight on 21 (72.41%) occasions and has a weighted average value of 181.03g.

Table 1. The Mode weight and weighted average values of the estimated resistance for different vessel types

Vessel Type	Mode Weight (% voted)	Weighted Average (g)
Healthy vessel	0 g (68.42%)	20.18
Narrowed vessel	100 g (40.00%)	97.14
Tortuous vessel	100 g (42.50%)	110.00
Vessel with calcified lesions	150 g (50.00%)	155.88
Occluded vessel	200 g (72.41%)	181.03

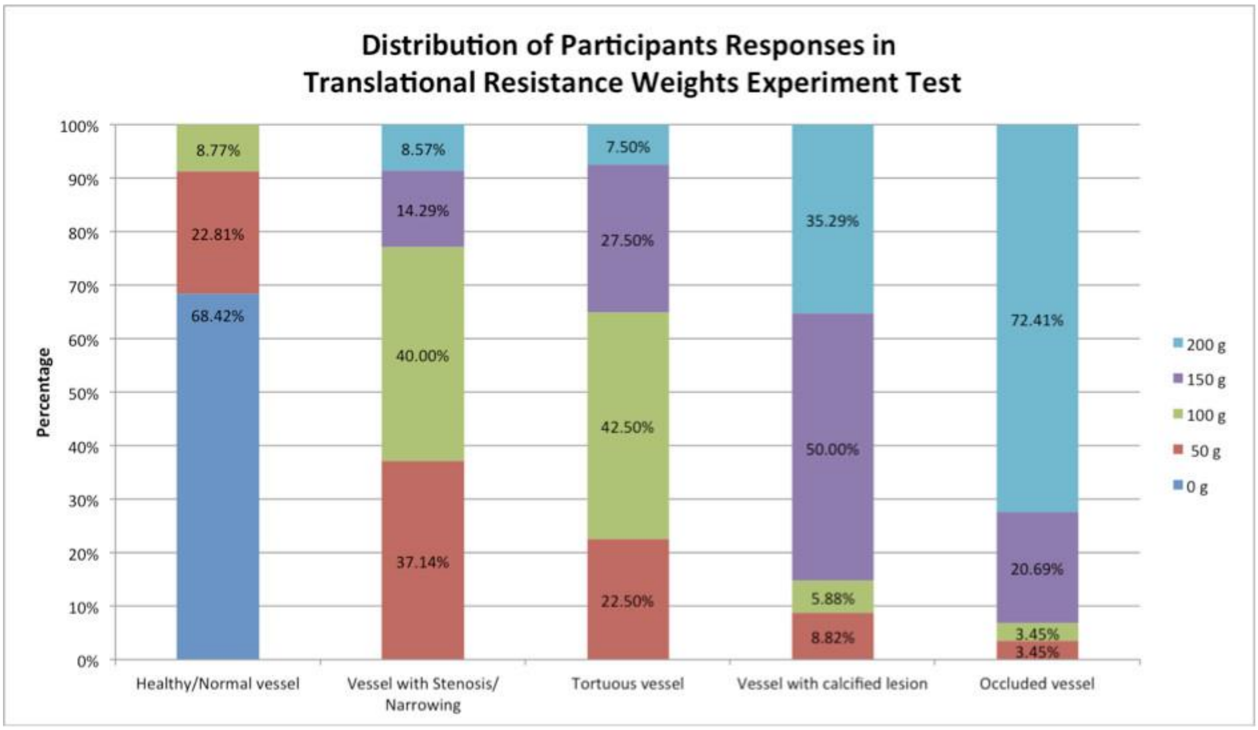

Figure 4 Participant Weights Experiment Responses

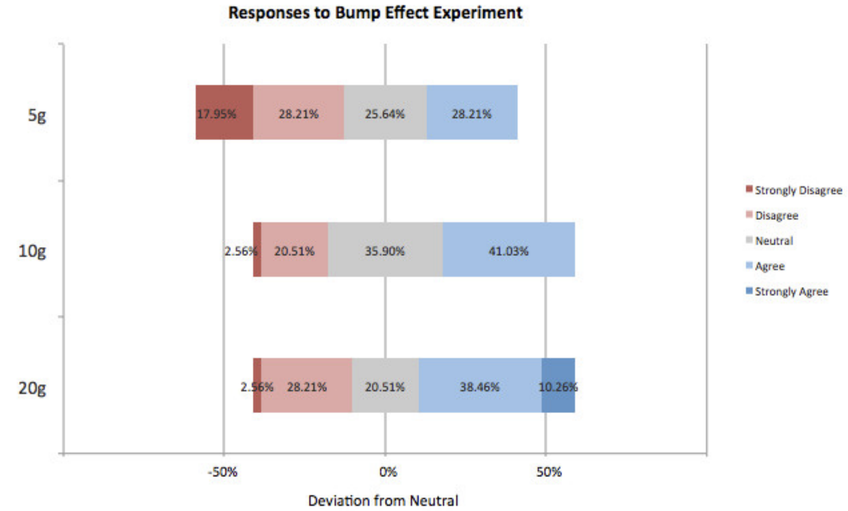

Figure 5 Participant Responses in Bump Effect Experiment

Bump Effect

Figure 5 shows the responses obtained for the bump effect. The 5g weight effect was negatively received since only 28.21 % of participants voted it as suitable, while 46.16 % disagreed/strongly disagreed. The 10g weight was more favored since 41.03% participants agreed and only 23.07 % disagreed/strongly disagreed, although more than a third of participants were undecided. Similarly, the 20g weight received the most agreement from 48.72% of participants but also received some disagreements from 30.76%. These findings would suggest that the range of forces could be between 10g-20g or 20g-30g.

DISCUSSION

Responses from the study suggest that translational resistance is the main haptic effect present in real-life endovascular interventions. This resistance is said to occur mainly in narrowed vessels (i.e. due to stenosis) and/or in tortuous vessels, but there is also the possibility of some form of subtle resistance present even in healthy and non-tortuous vessels. The resistance in narrowed vessels increases with the degree of narrowing and, in an occluded (cardiac) vessel, the resistance can potentially be sufficiently strong as to completely prevent instrument advancement. Similarly, the resistance felt in tortuous vessels increases with the degree of tortuosity. The direction of resistance felt in narrowed or tortuous vessels is most likely dependent on other factors such as instrument type, vessel physiology, type of stenosis, degree of tortuosity and others. In some cases, the resistance can only be felt when pushing or advancing the instrument, whereas in others, resistance may also be felt when retracting the instruments. The strength of the translational resistance effect and the estimated average force in varying vessel types in ascending order are: healthy vessel (20.18g/0.198N), vessel with stenosis (97.14g/0.953N), tortuous vessel (110g/1.08N), vessel with calcified lesions (155.88g/1.529N) and occluded vessels (181.03g/1.781N).

A majority of the study participants provided positive responses on the existence of rotational resistance felt in the manipulation of instruments within tortuous vessels. Most of the participants claim that this resistance effect is a result of the force or tension stored within the instrument as it is deformed and tries to regain its natural shape. Thus, the effect can be present even if the tortuous vessel is healthy. Rotational resistance may cause considerable loss of control of the instrument tip as it may take more than one turn of the instrument at the proximal end (closer to the operator) to produce an equivalent turn at the distal end. It is claimed that rotational resistance can normally be easily detected by observing fluoroscopic images, although the majority of participants commented that they feel the resistance first before it is visually evident. This would suggest that the importance of the visual detection of rotational resistance might depend on the specific vessel. For instance, vessels with higher tortuosity may produce stronger resistance, which would then be first detected through the sense of touch rather than through sight.

Regarding the bump effect, only a small majority of the participants agreed with the initial description of the effect as the result of the collision between the instrument and the vessel walls or bifurcations. It has been described as very noticeable, but also subtle and quick by some participants, while others describe it as the opposite. The subtleness of this particular effect makes its generalisation and understanding difficult, with more extensive investigations into its existence and characteristics needed to establish a more accurate range. From the experimental tests conducted, the forces involved could be as low as 0.05N. However, a relatively high percentage of the participants have estimated the bump effect to be between 0.1N and 0.2N. Similarly, questions regarding the existence of the heartbeat pressure received varied responses, with a large majority downplaying its importance in comparison to other haptic effects.

Ideally, the findings of the questionnaire and experimental study should be consistent and support each other. The experimental study indeed implied the existence of a translational resistance effect on the instruments, and that this resistance can be felt in both narrowed and tortuous vessels, with the strength of resistance increasing according to the degree of narrowing or tortuosity. In addition, the majority of participants agreed that there is no resistance in healthy and non-tortuous vessels, with those not agreeing, indicating that there is subtle resistance even in healthy and normal vessels, which was also reflected in the experimental results. The ranking of translational resistance obtained from the questionnaire and experimental study are similar. The lowest form of resistance is felt in healthy and non-tortuous vessels. This is followed by moderately strong resistance between 50g - 150g felt in tortuous vessels and in narrowed vessels with stenosis. In the questionnaire, participants rated the latter stronger than the former, but only just. The strongest form of translational resistance, found in vessels with calcified lesions and in occluded vessels, ranges between 150g - 200g, with occluded vessels providing the strongest level of resistance in both the questionnaire and the experimental study. Preferably only one of the weights would be voted as the correct weight used to produce the bump effect. However, the responses are very wide spread and none of the weights stands out as the most suitable representation of this type of haptic effect. This reflects the answers in the questionnaire, where there was also a large amount of uncertainty regarding the bump effect.

CONCLUSION

To the best of our knowledge, this is the first study of its kind explicitly investigating and attempting to quantify the different types of haptic effects present during endovascular interventions. The results expand current knowledge of haptic effects in endovascular interventions, highlighting possible shortcomings of present simulation-based core skills training techniques that are only able to provide limited haptic effects.

ACKNOWLEDGEMENT

The work presented in this paper was supported by the Malaysia-Imperial Doctoral Programme. We thank the BSIR for their assistance in recruiting participants and the dozens of surgeons/clinicians from various institutions within and outside the UK for their participation in the study.

REFERENCES

[1] K. Rangarajan et. al. " Systematic Review of Virtual Haptics in Surgical Simulation: A Valid Educational Tool? “, Journal of Surgical Education 2020; Vol. 77(2): 337-347.

[2] E. Abdi et. al., " Haptics in Teleoperated Medical Interventions: Force Measurement, Haptic Interfaces and Their Influence on User's Performance ", IEEE Transactions on Biomedical Engineering 2020; Vol. 67 (12): 3438 - 3451.

[3] Y. Song et. al. "Haptic Feedback in Robot-Assisted Endovascular Catheterisation", IEEE International Conference on Mechatronics and Automation 2017; 404-409.

[4] A. Amin, "High-Fidelity Endovascular Simulation," Techniques in Vascular and Interventional Radiology 2019; Vol. 22(1), 7-13.

[5] U. Karamchandani et al. "Training Surgeons to Perform Arthroscopic All-Inside Meniscal Repair: A Randomized Controlled Trial Evaluating the Effectiveness of a Novel Cognitive Task Analysis Teaching Tool, Imperial College London/University College London Meniscus Repair Cognitive Task Analysis (IUMeRCTA)," The American Journal of Sports Medicine 2021; Vol. 49(9): 2341-2350.

[6] C. Haitao et al. "*In vitro* and *in vivo* evaluation of 3D bioprinted small-diameter vasculature with smooth muscle and endothelium," Biofabrication ; Vol. 12(1), 1195-1202.

[7] Y. Wang et al. "Online measuring and evaluation of guidewire inserting resistance for robotic interventional surgery systems". Microsystem Technologies 2018, Vol. 24, 3467-3477.

[8] X. Jin et al. "Development of a Tactile Sensing Robot-Assisted System for Vascular Interventional Surgery". IEEE Sensors 2021, Vol. 21(10): 12284-12294.

[9] C. Hatzfeld et al. "Measurement setup to evaluate haptic interaction in catheterization procedures for training purposes." IEEE World Haptics Conference 2017; 412-417