**Systematic Review / Meta-analysis**

**Tool-tissue forces in surgery: A systematic review**

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**Keywords:** Tool-tissue interaction, Operative forces, Surgical forces, Force feedback, Force sensors, Haptic feedback, Smart instruments, Robotics, Robotic surgery

**ABSTRACT**

**Background:** Excessive tool-tissue interaction forces often result in tissue damage and intraoperative complications, while insufficient forces prevent the completion of the task. This review sought to explore the tool-tissue interaction forces exerted by instruments during surgery across different specialities, tissues, manoeuvres and experience levels.

**Materials & methods:** A PRISMA-guided systematic review was carried out using Embase, Medline and Web of Science databases.

**Results:** Of 462 articles screened, 45 studies discussing surgical tool-tissue forces were included. The studies were categorized into 9 different specialities with the mean of average forces lowest for ophthalmology (0.04N) and highest for orthopaedic surgery (210N). Nervous tissue required the least amount of force to manipulate (mean of average: 0.03N). When comparing differences in the mean of average forces between groups, novices exerted 22.7% more force than experts, and presence of a feedback mechanism (e.g. audio) reduced exerted forces by 47.9%.

**Conclusions:** The measurement of tool-tissue forces is a novel but rapidly expanding field. The range of forces applied varies according to surgical speciality, tissue, manoeuvre, operator experience and feedback provided. Knowledge of the safe range of surgical forces will improve surgical safety whilst maintaining effectiveness. Measuring forces during surgery may provide an objective metric for training and assessment. Development of smart instruments, robotics and integrated feedback systems will facilitate this.

1. **Introduction**

The field of surgery is defined by the application of physical force in order to manipulate or incise tissue for the treatment of medical disorders. Surgical forces must be applied judiciously, in a precise and controlled manner, in order to carry out procedures efficiently without causing unnecessary tissue injury [1–3]. The discrimination between appropriate and excessive force is a skill acquired over years of rigorous training, with junior surgeons tending to apply more force than more senior colleagues [4,5]. Indeed, up to half of the technical errors made by surgical trainees are related to the use of excessive force [6]. The advent of working hours restrictions and minimally invasive surgical approaches (often more technically demanding with steeper learning curves) may add to the challenge for surgical trainees [7,8].

The measurement of forces applied during surgery at a tool-tissue level is an important step in developing solutions to this problem and improving the safety of surgery. Force measurement can provide a quantitative metric of surgical skills, potentially useful for surgical training and assessment [4,9,10]. Measurement also allows the definition and characterization of a safe range of forces for specific manoeuvre [1,4]. These data can be used to generate surgical simulations for training [11] and develop devices (e.g. robotic platforms and smart instruments) with force feedback mechanisms [4,12–14,27].

Thus, we sought to understand the forces applied at the tool-tissue...
level for a range of surgical specialities, tissues, and manoeuvres. We also assessed the impact of operator experience and force feedback, through a systematic review of the literature.

2. Methods

A systematic review of the literature was performed in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) and AMSTAR (Assessing the methodological quality of systematic reviews) guidelines.

2.1. Search strategy and screening

Three databases were searched (EMBASE, MEDLINE and Web of Science) and using targeted search terms (Supplementary Table 1) as per the registered study protocol (PROSPERO ID: CRD42020170917). Articles (1950–2020) were searched on 12/05/2020 and duplicates were removed using Endnote X9. Inclusion criteria were: 1) studies reporting any open or laparoscopic surgical procedure performed on humans, cadavers, animals and validated models; 2) studies that described tool–tissue interaction forces measured directly. The inclusion of a simulation/model was based on whether it had proven face validity, content validity and construct validity (in the index study or in previous and cited work). Exclusion criteria were: reviews, editorials, non-English papers, full-text unavailability, unvalidated simulations and studies where no specific force values were recorded. Independent abstract screening was performed in duplicate by two authors (DZK, AKG). Review of full-text articles ensued according to the inclusion/exclusion criteria. Any discrepancies in selection were settled out by discussion and mutual agreement.

2.2. Data extraction and analysis

Data extracted from each eligible study included study demographics (continent, journal type), model characteristics (human/animal/synthetic, tissue type), procedure characteristics (surgical speciality, surgical task, instrument used), operator features (number, level of expertise) and force-related information (force measurement techniques, force levels, force-related complications). Adult surgical specialities (cardiothoracic surgery, otolaryngology, general surgery, plastic surgery, trauma and orthopaedic surgery, urology, neurosurgery, maxillofacial surgery) were defined as per Royal College of Surgeons guidelines.

3. Results

3.1. General characteristics

Screening of 462 articles resulted in the full-text appraisal of 73 studies selected for full-text review. Ultimately, 45 studies met the inclusion criteria and progressed to narrative and quantitative synthesis (Fig. 1). In regard to study demographics, all studies were primarily conducted at North American (n = 19) [2,4,14,17–33] or European (n = 26) [1,3,5,34–55] institutions (Supplementary Information 2). Articles were published in medical (n = 26) [2–4,14,21–23,25,27,29,35,36,43,46–49,51,53] or engineering (n = 19) [1,5,17–20,24,26,28,30–34,37–42,44,45,50,52,54,55] journals between 1999 and 2020 (Supplementary Information 3). Evidently, this is a new and expanding field, with more articles published in the last 5 years (n = 24) [2–4,14,17,19,22,23,25,26,28,32–35,39,41,45–47,50,53–55] than the previous 25 years combined (n = 21) [1,5,18,20,21,24,27–31,36–38,40,42–44,48,49,51,52] (Supplementary Information 3).

3.2. Summary forces for speciality

In terms of surgical speciality (Supplementary Information 2, Table 1), the highest proportion of studies (in-vivo and ex-vivo models) were in general surgery (n = 14, 31.1%) [3,5,20,26,27,29,35,38,41–43,49,51,54] with the majority of these involving laparoscopic procedures (n = 11) [3,5,26,34,38,41–43,49,54,55]; followed by neurosurgery (n = 13, 28.89%) [1,2,4,14,22,23,25,28,33,37,44,52], ophthalmology (n = 5, 11.11%) [17–19,21,32], cardiothoracic (n = 3, 6.67%) [26,30,53], vascular surgery (n = 3, 6.67%) [29,40,50], obstetrics & gynaecology (n = 2, 4.4%) [39,45], orthopaedics (n = 2, 4.4%) [47,48], otorhinolaryngology (n = 2, 4.4%) [36,46] and urology (n = 1, 2.2%) [24]. Ten studies (22.2%) involved robotic surgery platforms [1,14,17–19,22,26,29,48,55].

3.3. Summary forces for tissues systems and surgical manoeuvres

Across specialties and manoeuvres, nervous tissue (particularly the brain & retina) required the least amount of force to manipulate (mean of average 0.4N) [17–19,21,32], vascular (mean of average 0.07N) [29,40,50], neurosurgery (mean of average 0.68N) [1,2,4,14,22,23,25,28,33,37,44,52] and cardiothoracic surgery (mean of average 1.47N) [26,30,53]. Higher mean forces of averages, in ascending order, were seen in general surgery (mean of average 4.67N) [3,5,20,26,27,35,38,41–43,49,51,54], otorhinolaryngology (mean of average 8.49N) [36,46], obstetrics and gynaecology (mean of average 8.69N) [39,45], urology (mean of average 9.79N) [24] and orthopaedic surgery (mean of average 210N) [47,48].

3.4. Summary forces for tissues systems and surgical manoeuvres

Across specialties and manoeuvres, nervous tissue (particularly the brain & retina) required the least amount of force to manipulate (mean of average 0.4N, mean max 1.74N, n = 17) [1,2,4,17–19,21–23,25,28,32,33,37,44,52] with retinal forces always below 0.01N (Table 1) [17–19,21,32]. Mean forces applied on epithelial tissues were higher (mean of average 3.8N, mean max 9.7N, n = 18) [3,14,20,24,26,27,29,35,38,40–43,45,50,51,54], followed by muscle (mean of average 4.1N, mean max 6.7N, n = 3) [5,49,51], and connective tissue including bone (mean of average 45.8N, mean max 347.9N, n = 10) [20,26,30,31,36,39,46,48,53]. Mean forces per surgical manoeuvre are reported in Table 1 with drilling recording the highest forces (mean of average 14.1N, mean max 25.9N, n = 2) [46,48], whilst sharp dissection recorded the lowest (mean of average 0.03N, mean max not available, n = 1) [1]. The most recurrent tasks for the top 5 specialities (according to study number) are highlighted in Fig. 2.
3.4. Impact of experience and feedback

Eight studies compared novices (e.g. students) to intermediates (e.g. surgical trainees) or experts (e.g. consultant surgeons) (Table 3) [17,19,26,43,46,47,50,55]. When comparing the differences in the pooled mean of average forces exerted by experts and novices, novices exerted 22.7% (range 0–62%, n = 7) more force across tasks and specialities [17,19,26,43,46,47,50,55]. Two studies compared those with intermediate experience to novices and when comparing the differences in the mean of average force, novices applied 29% (range 29-29%, n = 2) more force [19,32]. When comparing experts with intermediates (3 studies), intermediates exerted on average 9.6% (range -50-50%, n = 3) more than experts [19,32,47]. However, in one of these studies experts applied significantly more force (200% of forces applied by intermediates) - with this study detailing forces during revision arthroplasty (screw extraction and implant extraction) where experts may have been more familiar with the significant amount of forces required to remove implants (and therefore less conservative) [47].

Additionally, 7 studies reported effects of feedback mechanisms on forces [5,17,18,32,35,39,43,55]. Feedback mechanisms were haptic (n = 3), visual (n = 2), tactile alone (n = 1) and audio (n = 1) based. Six studies compared feedback to no feedback [5,17,18,32,35,39,55], whilst one study compared visual feedback based on force and visual feedback based on time taken [43]. Pooled mean forces for all feedback mechanisms (across tasks, models and experience level) were reduced by 47.9% (pre-feedback 1.57N, post-feedback 0.8N). Table 2 details reported studies and the mean of average force feedback reports. Two studies aimed to establish the presence of a learning effect by measuring the forces applied before and after being trained on how to perform the task or by performing a series of tasks consecutively, and in both cases

Table 1
Summary forces averages across speciality, tissue type surgical tasks.

| Category          | Mean of average (N) | Mean of maximum (N) | Number of studies |
|-------------------|---------------------|---------------------|------------------|
| **Specialties**   |                     |                     |                  |
| Ophthalmology     | 0.04                | 0.05                | 5                |
| Vascular          | 0.07                | 0.65                | 3                |
| Neurosurgery      | 0.68                | 1.48                | 13               |
| Cardiothoracic    | 1.47                | 1.76                | 3                |
| General surgery   | 4.67                | 11.4                | 14               |
| Otorhinolaryngology | 8.49              | 15.6                | 2                |
| Obstetrics & gynaecology | 8.69     | 10.1                | 2                |
| Urology           | 9.79                | 15.6                | 1                |
| Orthopaedics      | 210                 | 1708                | 2                |
| **Tissues**       |                     |                     |                  |
| Nervous           | 0.4                 | 1.7                 | 17               |
| Epithelial        | 3.8                 | 9.7                 | 18               |
| Muscle            | 4.1                 | 6.7                 | 3                |
| Connective        | 45.8                | 347.9               | 10               |
| **Tasks**         |                     |                     |                  |
| Sharp dissection  | 0.03                | NA                  | 1                |
| Clamping          | 0.05                | 0.10                | 2                |
| Suction           | 0.13                | 0.21                | 1                |
| Coagulation       | 0.29                | 0.90                | 4                |
| Retraction without grasping | 0.95 | 2.51 | 3 |
| Blunt penetration | 1.21                | 3.58                | 4                |
| Blunt dissection  | 2.08                | 3.69                | 7                |
| Cutting           | 2.28                | 4.48                | 5                |
| Sharp penetration | 2.34                | 4.67                | 11               |
| Retraction with grasping | 3.65 | 10.25 | 13 |
| Drilling          | 14.09               | 25.99               | 2                |

Fig. 1. PRISMA flow chart of paper identification, screening and eventual inclusion.
the addition of a feedback system (visual or haptic) decreased the applied forces across the learning process when compared to no feedback [5,43]. One study explored the effect of toggling tactile feedback on both hands during a laparoscopic grasper task, finding that average forces exerted by the dominant hand were similar amongst the experts (3.5N, IQR: 3–4) and novices (3.5N, IQR: 3–4) without feedback and reduced by tactile feedback to a similar degree (experts 2.3, IQR: 1.4–3.3); (novices 2.2N, IQR: 1.5–2.7) [55]. However, novices applied greater force without tactile feedback with the non-dominant hand (novices 3.8N; experts 2.8N) being reduced again by a similar proportion with tactile feedback (novices by 71.1%; experts by 71.4%). This suggests that non-dominant forces exerted by novices can by reduced with tactile feedback to the levels (median 2.7N, IQR: 1.6–3.8) that experts would apply via the non-dominant hand without tactile feedback (median 2.8N, IQR: 1.8–4) [55].

4. Discussion

4.1. Principal findings

The measurement of tool-tissue forces during surgery is a new and expanding field, with early adopters including general surgery, neurosurgery and ophthalmology. Through this review, it is clear that the range of forces applied across specialities, tissues, and tasks is highly variable. The highest forces are seen in specialities requiring bony drilling (orthopaedic) and abdominal organ manipulation (urology) [24, 47,48]. Whilst lowest forces are seen in specialities encountering more delicate tissue – ophthalmology, neurosurgery and vascular surgery [1,
providing feedback based on this to the surgeon [12]. Such instruments factors on operative performance (e.g. fatigue, personal stress) could based on established force safety systems) [12,13]. Surgeons could use made more high fidelity (for example, designing alerting mechanisms surgical procedure [12]. This technology can be employed in isolated the surgeon have shown potential in decreasing the exerted forces (independently of retraction tissue) [12,55]. Using this data to assess the effect of human workflow or devices, may improve the safety of surgery [12]. This is applicable forces based on tissue type, and building this into operative review contains many studies using phantom models to simulate oper measurement and use of intra-operative force data in real-time. Smart force- indeed, examining force data in the context of intra-operative errors affecting complications arising from applying too much force. Generally, expert surgeons tend to apply less force than novice and intermediate surgeons, and operators tend to apply less force after repeating the task consecutively [17,19,26,43,46,47,50,55]. A caveat to this was when applying extremes of forces (e.g. arthroplasty implant removal), where senior surgeons tend to apply slightly more forces than novice and intermediate surgeons, perhaps due to their confidence (in applying necessary forces and in handling novel devices) [19,47]. Feedback of any modality (haptic, visual, audio) decreases experience levels on force exertion.

| Study   | Task                | Speciality                     | Mean of Average Forces Novice | Mean of Average Forces Intermediate | Mean of Average Forces Expert | % Difference Novice Vs Intermediate | % Difference Novice Vs Expert | % Difference Intermediate Vs Expert |
|---------|---------------------|--------------------------------|-------------------------------|-------------------------------------|-----------------------------|------------------------------------|-------------------------------|----------------------------------|
| Horeman 2012 | Sharp penetration Drilling | General surgery (laparoscopic) | 4.5                           | 2.7                                 | 40% more                   |                                    |                               |                                  |
| Kohler 2015   | Retraction with Grasping | Otolaryngology                 | 13.85                         | 12.29                               | 11% more                    |                                    |                               |                                  |
| Wottawa 2016 | Retraction with Grasping | General surgery (laparoscopic) | 3.65                          | 3.15                                | 14% more                    |                                    |                               |                                  |
| Gonenc 2017   | Sharp penetration Drilling | Ophthalmology (robotic)        | 0.05                          | 0.07                                | 29% more                    | 0% more                            | 29% more                       |                                  |
| Raffi-Tari 2017 | Sharp penetration Drilling | Vascular surgery               | 0.32                          | 0.12                                | 62% more                    |                                    |                               |                                  |
| Talasaz 2017   | Sharp penetration Drilling | Cardiothoracic surgery (robotic) | 2.54                      | 2.49                                | 2% more                     |                                    |                               |                                  |
| Ebrahimzadeh 2019 | Sharp penetration Drilling | Ophthalmology (robotic)        | 0.10                          | 0.14                                | 29% more                    | 30% more                            | 50% more                       |                                  |
| Kwong 2019     | Retraction with grasping | Orthopaedic                    | 470.7                         | 941.4                               | 50% less                    |                                    |                               |                                  |

2,4,14,17–19,21–23,25,28,29,32,33,37,40,44,50,52]. There is a relative paucity in data regarding the complications arising from applying too much force. Generally, expert surgeons tend to apply less force than novice and intermediate surgeons, and operators tend to apply less force after repeating the task consecutively [17,19,26,43,46,47,50,55]. A caveat to this was when applying extremes of forces (e.g. arthroplasty implant removal), where senior surgeons tend to apply slightly more forces than novice and intermediate surgeons, perhaps due to their confidence (in applying necessary forces and in handling novel devices) [19,47]. Feedback of any modality (haptic, visual, audio) decreases exerted forces by all users (across experience levels) [5,17,18,32,35,39,43,55].

4.2. Findings in the context of literature

The measurement of intraoperative tool-tissue forces may have multiple utilities in the future of surgery. Firstly, in terms of training and assessment, force metrics (average forces, maximum forces, time spent over threshold force, etc) may provide objective data regarding surgeon skill level and therefore may be used as a tool for learning [4,9,10]. Our review contains many studies using phantom models to simulate operations – with tool-tissue force data, these could be refined further and made more high fidelity (for example, designing alerting mechanisms based on established force safety systems) [12,13]. Surgeons could use force data to facilitate reflection on technique and highlighting unconscious excessive force use (e.g. with the non-dominant hand whilst retracting tissue) [12,55]. Using this data to assess the effect of human factors on operative performance (e.g. fatigue, personal stress) could facilitate the development of supportive work environments which optimise surgical care [56,57].

Indeed, examining force data in the context of intra-operative errors and post-operative outcomes may provide an added layer of granularity to this reflection on performance [4]. Establishing the safe thresholds of applicable forces based on tissue type, and building this into operative workflow or devices, may improve the safety of surgery [12]. This is particularly important in laparoscopic and endoscopic surgery, where lack of depth perception, tool friction, motion scaling, mirroring effects and the size of available force sensors, make it difficult to estimate the forces exerted at the tip of the instruments [58].

Additionally, the development of novel technology will allow measurement and use of intra-operative force data in real-time. Smart force-limiting instruments are one such example, measuring forces, and providing feedback based on this to the surgeon [12]. Such instruments have shown potential in decreasing the exerted forces (independently of the surgeon’s grade) while not significantly disturbing the flow of the surgical procedure [12]. This technology can be employed in isolated instruments or as part of robotic platforms [59]. Although the sensing of forces within these platforms has been refined, using these forces to provide second-by-second surgeon feedback (particularly haptic) has proven difficult in the current generation of systems used in clinical practice [59,60]. In experimental, ex vivo studies, however, the use of robotic platforms with inbuilt force feedback mechanisms have shown promise in improving surgical performance and increasing surgical safety (e.g. decreased tissue damage) – particularly for less experienced surgeons [55,61].

4.3. Limitations and strengths

The main limitation of this review is the heterogeneity of data, making the synthesis and comparison of studies difficult. Reported force values were variable, with some studies using mean/median forces, some maximum forces, and others reporting the root mean square values. Very few studies were matched for tissue or model type (with a relative paucity of in-vivo human studies), or for procedure or task. A standardised data set for reporting, developed by e.g. a consensus process, may prove useful in aligning research going forward. Additionally, the majority of experiments comparing experts and novices assessed each group using the same surgical task (Supplementary material 2) [17,19,26,43,46,47,50,55]. However, when considering future study design and practical translations of comparing experts to novices, recognising that novices and expert surgeons may not complete the same parts of the operation is an important factor to consider. Furthermore, only a minority of included studies were in-human and explored complications related to excess force (e.g. sharp or blunt damage to surrounding tissues or vessels) or insufficient force (e.g. delayed or incomplete task completion), which has clear clinical implications and is an important area for further research [3,4]. Finally, in this review we solely considered the forces measured directly since the models designed to measure forces indirectly were often not validated or they did not report a specific force value. In the future, comparing forces measured directly with those measured indirectly would offer a valuable insight into the accuracy of these models when estimating actual forces from the forces applied by the surgeon to the tool or from the alteration in the tissue shape.

5. Conclusion

The measurement of tool-tissue forces during surgery is an expanding field. In the context of heterogeneous data reporting and study design, neurosurgery, ophthalmology and vascular surgery require the least amount of force, whilst orthopaedic surgery required the most. Accordingly, nervous tissue was the most delicate, whilst connective

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Table 3
Overview of impact of experience levels on force exertion.
tissue required more force to manipulate. Generally, experts apply less force, and trainees benefit more from force feedback. Looking forward, standardised reporting of tool-tissue interactions will facilitate pooled analysis of force safety thresholds and performance metrics. Development of novel technology such as smart instruments and robotics will facilitate, and benefit from, these advancements.

Ethical approval

Ethical approval was unnecessary due to the nature of the study (systematic review).

Author contribution

AKG: data collection, data analysis, manuscript drafting. DZK: study design, data collection, data analysis, manuscript drafting, critical revisions. GPM: study design, data analysis, manuscript drafting, critical revisions. HJM: study design, data analysis, manuscript drafting, critical revisions.

Research registration number

1. Name of the registry: PROSPERO.
2. Unique Identifying number or registration ID: CRD42020170917.
3. Hyperlink to your specific registration (must be publicly accessible and will be checked): https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=170917.

Guarantor

George P Mylonas and Hani J Marcus are joint senior authors and guarantors for this study.

Provenance and peer review

Not commissioned, externally peer-reviewed.

Patient anonymity and informed consent

Not applicable due to the nature of the study (systematic review).

Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declaration of competing interest

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as hono-
raria; educational grants; participation in speakers’ bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jamsu.2021.102268.

References

[1] H.J. Marcus, K. Zareinia, L.S. Gan, et al., Forces exerted during microsurgery: a cadaver study, Int. J. Med. Robot. Comput. Assist. Surg. 10 (2) (2014) 251–256.
[2] L.S. Gan, K. Zareinia, S. Lama, et al., Quantification of forces during a neurological procedure: a pilot study, World Neurosurg 84 (2) (2015) 537–548.
[3] J. Barrie, L. Russell, A.J. Hood, et al., An in vivo analysis of safe laparoscopic grasping thresholds for colorectal surgery, Surg. Endosc. 32 (10) (2018) 4244–4250.
[4] T. Sugiyama, S. Lama, L.S. Gan, et al., Forces of tool-tissue interaction to assess surgical skill level, JAMA Surg 153 (3) (2018) 234–242.
[5] T. Horeman, J. Dankelman, F.W. Jansen, et al., Assessment of laparoscopic skills based on force and motion parameters, IEEE (Int. Electr. Electron. Eng.) Trans. Biomed. Eng. 61 (3) (2014) 805-813.
[6] B. Tang, G.B. Hanna, A. Cuscheri, Analysis of errors enacted by surgical trainees during skills training courses, Surgery 138 (1) (2005) 14–20.
[7] N. Ahmed, K.S. Devitt, I. Keshet, et al., A systematic review of the effects of resident duty hour restrictions in surgery: impact on resident wellness, training, and patient outcomes, Ann. Surg. 259 (6) (2014) 1041.
[8] J.A. Sclafani, C.W. Kim, Complications associated with the initial learning curve of minimally invasive spine surgery: a systematic review, Clin. Orthop. Relat. Res.® 472 (6) (2014) 1711–1717.
[9] K. Hazada, A. Morita, Y. Minakawa, et al., Assessing microneurosurgical skill with medico-engineering technology, World Neurosurg 84 (4) (2015) 964–971.
[10] A.L. Trejos, R.V. Patel, R.A. Malthaner, et al., Development of force-based metrics for skills assessment in minimally invasive surgery, Surg. Endosc. 28 (7) (2014) 2106–2119.
[11] H. Azarnoush, S. Sia, R. Sawaya, et al., The force pyramid: a spatial analysis of force application during virtual reality brain tumor resection, J. Neurosurg. 127 (1) (2016) 171-181.
[12] C.J. Payne, H.J. Marcus, G.-Z. Yang, A smart haptic hand-held device for neurological microdissection, Ann. Biomed. Eng. 43 (9) (2015) 2185–2195.
[13] T.P. Cundy, E. Thangaraj, H. Rafii-Tari, et al., Force-sensing enhanced simulation environment (ForSense) for laparoscopic surgery training and assessment, Surgery 157 (4) (2015) 723–731.
[14] G.R. Sutherland, Y. Maddahi, L.S. Gan, et al., Robots in the neurological treatment of glioma, Surg. Neurol. Int. 6 (Suppl 1) (2015) S1.
[15] A.S. Carr, C. Munuch, S. Bugge, et al., Core surgical training and progression into specialty surgical training: how do we get the balance right? Bull. Roy. Coll. Surg. Engl. 93 (7) (2011) 244–248.
[16] RCoS. England, Surgical Specialties, Available at: https://www.rcseng.ac.uk/career-in-surgery/trainees/foundation-and-core-trainees/surgical-specialties/, 2020. (Accessed 1 September 2020).
[17] A. Ebrahimi, C. He, N. Patel, et al., Sclera Force Control in Robot-Assisted Eye Surgery. Adaptive Force Control vs. Auditory Feedback, IEEE, 2019, pp. 1–7.
[18] B. Gonenc, M.A. Balicki, J. Handa, et al., Preliminary Evaluation of a Micro-force Sensing Handheld Robot for Vitreoretinal Surgery, IEEE, 2012, pp. 4125–4130.
[19] B. Gonenc, J. Char, P. Gehlbach, et al., Towards robot-assisted retinal vein cannulation: a motorized force-sensing microneedle integrated with a handheld micromanipulator, Sensors 17 (10) (2017) 2195.
[20] A. Goyzueta, C. Nelson, B. Woodin, et al., Experimental analysis of jaw-tissue interaction forces using a compliant surgical grasper, J. Med. Dev. Trans. ASME 7 (2) (2013).
[21] P.K. Gupta, P.S. Jensen, E. de Juan, Surgical Forces and Tactile Perception during Retinal Microsurgery, Springer, 1999, pp. 1218–1225.
[22] Y. Maddahi, I.S. Gan, K. Zareinia, et al., Quantifying workspace and forces of surgical dissection during robot-assisted neurosurgery, Int. J. Med. Robot. Comput. Assist. Surg. 12 (3) (2016) 528–537.
[23] Y. Maddahi, A. Ghasemloonia, K. Zareinia, et al., Quantifying force and positional frequency bands in neurological tasks, J. Robot. Surg. 10 (2) (2016) 97–102.
[24] T. Podder, D. Clark, J. Sherman, et al., In vivo motion and force measurement of surgical needle intervention during prostate brachytherapy, Med. Phys. 33 (8) (2006) 2915–2922.
[25] T. Sugiyama, L.S. Gan, K. Zareinia, et al., Tool-tissue interaction forces in brain arteriovenous malformation surgery, World Neurosurg. 102 (2017) 221–228.
[26] A. Talasar, A.L. Trejos, R.V. Patel, The role of direct and virtual force feedback in suturing using a 7-DOF dual-arm teleoperated system, IEEE Trans. Haptics 10 (2) (2016) 276–287.
[27] A.L. Trejos, S. Jayaraman, R.V. Patel, et al., Force sensing in natural orifice transluminal endoscopic surgery, Surg. Endosc. 25 (1) (2011) 186–192.
[28] K.G. Wang, K. Grant, Q. Sun, et al., Development of an Instrumented Surgical Setup for Quantifying Displacement and Force in Surgical Dissection, vol. 57380, American Society of Mechanical Engineers, 2015, V003T03A032.
[29] D. Ye, H. Mozaffari-Naeini, C. Busart, et al., MEMSurgery: an integrated test-bed for vascular surgery, Int. J. Med. Robot. Comput. Assist. Surg. 1 (3) (2005) 21–30.
[30] M.C. Yip, S.G. Yuen, R.D. Hove, A robust uniaxial force sensor for minimally invasive surgery, IEEE Trans. Biomed. Eng. 57 (5) (2010) 1008–1011.
J.-P. Kobler, S. Wall, G.J. Lexow, et al., An experimental evaluation of loads occurring during guided drilling for cochlear implantation, Int. J. Comput. Assist. Radiol. surg. 10 (10) (2015) 1625–1637.

L. Kwong, F. Billi, S. Keller, et al., A comparative study between the Stryker EZout powered acetabular revision system and the zimmer explant acetabular cup removal systems, Tech. Orthop. (2020).

T. Ortmaier, H. Weiss, S. Döbele, et al., Experiments on robot-assisted navigated drilling and milling of bones for pedicle screw placement, Int. J. Med. Robot. Comput. Assist. Surg. 2 (4) (2006) 350–363.

G. Picod, A.C. Jambon, D. Vinatier, et al., What can the operator actually feel when performing a laparoscopy? Surg. Endosc. Other Intervent. Tech. 19 (1) (2005) 95–100.

H. Rafii-Tari, C.J. Payne, C. Ricknell, et al., Objective assessment of endovascular navigation skills with force sensing, Ann. Biomed. Eng. 45 (5) (2017) 1315–1327.

S.P. Rodrigues, T. Horeman, J. Dankelman, et al., Suturing intraabdominal organs: when do we cause tissue damage? Surg. Endosc. 26 (4) (2012) 1005–1009.

A.A. Sharp, A.M. Ortega, D. Restrepo, et al., In vivo penetration mechanics and mechanical properties of mouse brain tissue at micrometer scales, IEEE Trans. Biomed. Eng. 56 (1) (2008) 45–53.

M. Sümer, M.C. Ozin, T. Eray, et al., The undamaged tissue grasping in a laparoscopic surgical grasper via distributed pressure measurement, Tribol. Int. 113 (2017) 330–337.

A.K. Golahmadi et al., Enabling Safe Robot-Assisted Vitreoretinal Surgery, IEEE, 2018, pp. 1239–1241.

C.C.J. Alleblas, M.P.H. Vleugels, S.F.P.J. Coppus, et al., The effects of laparoscopic graspers with enhanced haptic feedback on applied forces: a randomized comparison with conventional graspers, Surg. Endosc. 31 (12) (2017) 5411–5417.