



UNIVERSITY OF LEEDS

This is a repository copy of *A systematic examination of preoperative surgery warm-up routines*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/105184/>

Version: Accepted Version

Article:

Pike, TW, Pathak, S, Mushtaq, F orcid.org/0000-0001-7881-1127 et al. (3 more authors)
(2017) *A systematic examination of preoperative surgery warm-up routines*. *Surgical Endoscopy*, 31 (5). pp. 2202-2214. ISSN 0930-2794

<https://doi.org/10.1007/s00464-016-5218-x>

© 2016 Springer Science+Business Media New York. This is an author produced version of a paper published in *Surgical Endoscopy*. The final publication is available at Springer via <http://dx.doi.org/10.1007/s00464-016-5218-x>. Uploaded in accordance with the publisher's self-archiving policy.

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

A systematic examination of preoperative surgery warm-up routines

T W Pike MSc MRCS^{1,2}, S Pathak MSc MRCS¹, F Mushtaq PhD^{*2}, R M Wilkie PhD², M Mon-Williams PhD², J P A Lodge MD FRCS¹.

¹Department of HB & Transplant Surgery, St James's University Hospital, Leeds, LS9 7TF, United Kingdom.

²School of Psychology, Faculty of Medicine & Health, University of Leeds, LS2 9JT, United Kingdom.

*Correspondence can be addressed to Faisal Mushtaq at the School of Psychology, Faculty of Medicine & Health, University of Leeds, Leeds, LS2 9JT, UK. Email: f.mushtaq@leeds.ac.uk. Tel: +44 (0) 113 3433 640.

Manuscript type: Systematic Review

Manuscript length: 4080 words

Number of figures: 1

Number of tables: 9

Running head: What makes an effective warm-up?

Key words: Warm-up, Surgery, Preoperative simulation, Performance

Abstract

Background: Recent evidence indicates that a preoperative warm-up is a potentially useful tool in facilitating performance. But what factors drive such improvements and how should a warm-up be implemented?

Methods: In order to address these issues, we adopted a two-pronged approach: (i) we conducted a systematic review of the literature to identify existing studies utilizing preoperative simulation techniques; (ii) we performed task analysis to identify the constituent parts of effective warm-ups. We identified five randomised control trials, four randomised crossover trials and four case series. The majority of these studies reviewed surgical performance following preoperative simulation relative to performance without simulation.

Results: Four studies reported outcome measures in real patients and the remainder reported simulated outcome measures. All but one of the studies found that preoperative simulation improves operative outcomes- but this improvement was not found across all measured parameters. Whilst the reviewed studies had a number of methodological issues, the global data indicate that preoperative simulation has substantial potential to improve surgical performance. Analysis of the task characteristics of successful interventions indicated that the majority of these studies employed warm-ups that focused on the visual motor elements of surgery. However, there was no theoretical or empirical basis to inform the design of the intervention in any of these studies.

Conclusions: There is an urgent need for a more rigorous approach to the development of 'warm-up' routines if the potential value of preoperative simulation is to be understood and realised. We propose that such interventions need to be grounded in theory and empirical evidence on human motor performance.

1 Introduction

2 Introduction

It is widely acknowledged that there are few systemic protection mechanisms that can prevent the occurrence of technical error in surgery[1]. A recent survey of practicing surgeons indicated that technical errors are common in the operating theatre (although they are often unreported) [2]. It has become increasingly more challenging to address the prevalence of technical error for a variety of reasons. These reasons include an increased emphasis on minimally invasive surgery - which is a more technically demanding task compared to open surgery. In parallel, there has been a reduction in training hours[3] (see the impact of the European Working Time Directive[4] and the Modernising Medical Careers report[5] on United Kingdom training programs) and these changes have been mirrored in the United States[6] and Canada[7], among others.

How can we address these issues within health services that explicitly state that patient safety is their overarching priority[8, 9]? One solution seems to lie in simulation. The substantial reduction in training time, alongside the increasing complexity of surgical procedures, has driven an exponential increase in the use of simulation for education. The approach is promising - there is some evidence to suggest that skills learnt in simulated environments can transfer into the operating room[10, 11] - greatly enhancing potential learning opportunities for trainees. **The nature of surgical simulators enables substantially more practice relative to the traditional models of surgical education.** The rationale is that increased exposure to procedures in a controlled environment should reduce the amount of technical errors in surgery over the long-term - a claim that remains to be empirically established.

More recently, researchers have been investigating whether these simulators might yield shorter-term gains for trainees and experts alike, through the implementation of pre-operative “warm-ups” [12, 13]. The idea of warming up for surgery has largely been borrowed from sports medicine: there is a long history of elite athletes performing warm-up

routines. The benefits of warm-up appear to extend to areas beyond sport - for example, opera singers warm their vocal chords before singing to an audience. In surgery, recent systematic reviews of the literature indicate that warming up (most often on a surgical simulator- we refer to this process as “preoperative simulation”) is an approach that improves a surgeon’s performance in the operating room. Whilst the evidence is promising, and the analogy appears to fit well - after all, surgery is a task that demands a high level of performance (with substantial risks associated with task failure), there is no clear understanding of *how* a warm-up might benefit the specific demands of surgery. This is a serious shortcoming and a key barrier to its implementation.

A poorly designed warm-up routine could potentially have a plethora of negative consequences: from wasting precious clinical time to negatively impacting on performance in the operating theatre. If the potential of warming up is to be realised, we need a careful consideration of the processes that facilitate performance. To this end, we adopted a dual-processing framework from cognitive science to interrogate warm-up methodologies to identify their constituent parts.

Surgical performance can broadly be separated into two types: (i) low level ‘motor decisions’ such as the completion of a planned sequence of actions, mastered through repetitive practice; and (ii) comparably higher-level offline ‘cognitive decisions’ generated through education and experience. The majority of human behaviour can be understood as the product of a complex interplay between cognition and motor control[14], with neuroimaging evidence indicating overlapping cortical and subcortical networks[15–18]. In surgery, this interaction can manifest itself in multiple ways: knowing the procedural steps necessary to complete an operation without the requisite manual dexterity can be disastrous. Conversely, motor proficiency without appropriate understanding or attention is equally problematic.

Based on this perspective on human performance, there are good theoretical reasons for why preoperative simulation might prove to be effective. Preoperative simulation

could be used to engage cognitive and motor processes in a variety of ways. For example, physically rehearsing an operation before performing that procedure *in vivo* could allow surgeons to rapidly refine, update and actively engage internal models of the external world to promote successful actions: facilitating recall of the sequence of steps required during the operation as well as rehearsing strategies that could be deployed if complications arise. Additionally, or even alternatively, the use of preoperative simulation that focuses on visual motor processes might assist surgeons in calibrating their motor system to the visual and motoric transformations inherent in minimally invasive surgery.

To understand the processes driving effective warm-up, we conducted a systematic review of the literature on preparation and surgical success. After identifying studies examining the efficacy of warm-up, we considered the task characteristics of a successful warm-up and the performance metrics that are modulated by this process.

3 Methods

We developed a search strategy according to the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidance[19]. In order to ensure comprehensive coverage of the areas related to this research question, we conducted an electronic search of relevant databases (Cochrane Library (1995-), PubMed, PsycINFO (1967-), ERIC (1964-) and Google Scholar) utilising the following key words: “Surgery”, “Laparoscop*”, “Minimally Invasive”, “Simulat*”, “Educat*”, “Technolog*”, “Warm-up”, “Warm-up”, “Preparation”, “Planning”, “Rehearsal”, “Mental Rehearsal”, “Cognitive”, “Decision Making”, “Decision”, “Outcome”, “Performance”, “Preoperative” and “Pre-operative”. Key words were grouped using “AND” or “OR” terms. Bibliographies of relevant studies and the “related articles” link in PubMed were used to identify any additional studies. All citations and abstracts identified were thoroughly reviewed. The last date for this search was 1st May 2015.

3.1 Inclusion and Exclusion Criteria

All included studies analysed the effect that a preoperative simulation had on subsequent surgical performance (simulated or real-life). Studies were restricted to those that examined a deliberate intervention prior to an operation or procedure rather than a training regime or educational programme. There was no restriction applied to the type of skills examined. All study designs were considered for inclusion. Studies published only as an abstract or unpublished report were excluded from further analysis. All studies were carefully evaluated for duplication or overlapping data and such reports were removed.

3.2 Study Selection

Two authors (TWP and SP) independently performed the search according to the strategy described above. Both authors independently reviewed the identified abstracts and

excluded those that did not meet the inclusion criteria. If no abstract was available or the abstract did not contain adequate information, the full article was reviewed. Differences of opinion between the two authors (TWP and SP) on the selection of studies were resolved by consensus with the senior author (JPAL). If consensus could not be reached the protocol indicated that the senior author's decision would be considered final – a process that was not required during study selection.

3.3 Data Extraction, Outcome Measures and Statistical Analysis

Authors TWP and SP, using a standardised proforma, performed data extraction independently. As with study selection, the research protocol indicated that disagreements would be resolved by consensus with the senior author (JPAL). The following parameters were recorded: study characteristics (first author, year of publication, place of publication), population characteristics and outcomes of interest. The primary outcome of interest was surgical performance, however defined. Of secondary interest were the additional outcome measures reported by each study. The heterogeneity of included studies prevented a quantitative synthesis of reported outcomes. Finally, to understand the key drivers for effective warm-up, we also examined the characteristics of the warm-up task.

3.4 Risk of Bias Assessment

The method for objectively assessing the risk of bias of included studies depended on the type of study. Randomised control trials were reviewed using the Cochrane risk of bias tool[20], while cross-over trials were analyzed using a modified version of a tool developed by Mills et al. [21].

4 Results

Four hundred and eighty-three articles were identified by the search strategy described above. Following a review abstracts, full articles and references, 13 studies were included in this systematic review (see **Figure 1**).

---INSERT FIGURE 1 HERE---

Figure 1. PRISMA flow chart showing the selection of articles for review

4.1 Study Characteristics

Four randomised control trials (RCTs)[22–25] and four randomised cross-over studies[26–29] were included- all of which reviewed operative outcomes following a practice of technical skills prior to an operation versus no practice. A further four studies were case studies, two compared a technical skills practice to no practice[30, 31] and two[32, 33] did not contain a control group. One RCT[34] examined the effect of mental practice prior to an operation on subsequent laparoscopic performance.

Eight of the studies[22, 24, 25, 29–31, 33, 34] (45,47,48,52-54,56,57) examined the effect of preoperative simulation on general surgery procedures, three looked at obstetrics and gynaecological procedures[23, 26, 32] and the last two examined the effect of preoperative simulation on endovascular[27] and urological[28] procedures. Four of the studies[22, 28–30] examined outcomes in real patients, the other nine[23–27, 31–34] reviewed simulated outcomes.

4.2 Assessment of Bias

There was significant variability in the quality of studies included. Only one study[25] was judged to be at low risk of bias: **Table 1, 2**. Five studies[22, 23, 25, 26, 29] were found

to be at low risk of randomisation bias, with explicit detailing of the methods of randomisation and allocation concealment employed. Two studies[22, 25] reported a *priori* power calculations, but one of these studies[22] calculated that a substantially larger number of participants would be required than were actually recruited- thus indicating a lack of statistical power in this study. Relatedly, the sample sizes across all studies was generally modest, with only one RCT or cross-over study[25] reporting more than 20 participants per group. The included case studies could not be objectively assessed by the methods used to review the RCTs and cross-over studies, but each demonstrated methodological shortcomings, as discussed below.

---INSERT TABLE 1 & 2 HERE---

4.3 Reported Outcomes

The included articles report 103 different outcome metrics, often combined to form a compound score. A summary of the main findings of each study is detailed in **Table 3**. Twelve[23–34] of the thirteen included manuscripts concluded that a preoperative simulation improves subsequent surgical performance. Importantly, no study found preoperative simulation to have a detrimental effect on surgical performance or suggested any negative aspect of preoperative simulation.

---INSERT TABLE 3 HERE---

4.4 Studies Reporting Global Rating Score

The most often reported outcome was the effect of preoperative simulation on a global rating score of performance. Seven of the included studies[22, 23, 27–30, 34] reported this outcome metric - defined as a summary of objective assessment parameters by an expert examiner. Nine global rating scales[22, 23, 25, 35–41] were employed in the seven studies, with all but two studies reporting a different global rating scale. In a majority of studies, validated global rating assessments were used. In three studies[22, 28, 30] a

modification of a previously published global rating scale was employed.

In two RCTs[23, 34] and one cross-over trial[29], the authors reported unequivocally that preoperative simulation improves subsequent real-world operative performance, as assessed by a global rating scale. Two cross-over trials[27, 29] reported ambiguous findings for the effect of preoperative simulation on surgical performance; the first study[27] reported a significant effect as measured by one global rating scale, but no effect according to another also-reported scale. The second study[28] found a significant improvement in one assessed task, but not another. One RCT[22] and one cross-over trial[30] found that preoperative simulation had no effect on subsequent performance, as judged by a global rating scale.

4.5 Studies Reporting Performance Time

Five of the included studies[24, 25, 27, 31, 33] reported 'pure' performance time-defined as the time taken to perform an assessed task. Those articles that reported duration as part of a global rating scale were not included as such studies have been discussed above. The authors in one RCT[25] and one case study[26] reported that preoperative simulation shortens subsequent performance time in a simulated environment. In one cross-over trial[27] and one case study[33] equivocal results were reported, with preoperative simulation reducing the time of some performance metrics, but not all. Finally, in only one RCT[24] did preoperative simulation not affect the time taken to perform simulated laparoscopic surgery.

4.6 Studies Reporting Time-based Score

In three studies[26, 31, 32] a time-based score was reported, either in combination with errors made (resulting in a time penalty) or as the number of occasions a task was performed within a set time. The authors in one case study[32] found that preoperative simulation increases the number of times a laparoscopic task can be performed within a set

time period. The authors in another case study[31] found that preoperative simulation reduces time taken and errors made during the placement of intracorporeal sutures, but not the time taken and errors made during two other laparoscopic tasks. Finally, in one cross-over study[26] it was found that preoperative simulation did not improve simulated laparoscopic performance as assessed by a time-based score.

4.7 Kinematic performance

The authors of four studies[24, 25, 28, 33] reported outcome metrics generated by the laparoscopic simulator used during their experiments. Hand and tool movement smoothness and instrument path length were reported, but there was no concordance across the studies; some reported significant results in certain outcome metrics while others did not.

4.7.1 Error frequency

In four studies[24, 25, 28, 33] the effect of preoperative simulation on the number of errors made during a procedure (determined by a simulator or expert assessor) was reported. The authors of one RCT[24] and one case study[33] found that preoperative simulation significantly reduced the number of errors that occurred during simulated laparoscopic performance. Conversely, another RCT[25] found that preoperative simulation did not affect error frequency.

4.8 Subjective Evaluation

The authors of one cross-over study[27] explored participants' perception of how useful they found the preoperative simulation and whether they believed simulation improved their subsequent performance. This was assessed by a questionnaire utilising a five-point Likert scale. Participants reported that they felt patient-specific simulation to be more helpful than generic simulation, which was more useful than no simulation. Participants also reported that they felt patient-specific simulation helped with decision-making, improved

safety, increased their confidence levels and resulted in reduced preoperative anxiety (of the operator).

4.9 Studies Examining Outcomes in Real Patients

In four studies[22, 28–30], the effect of preoperative simulation on real patients was examined. Three of these studies[28–30] concluded that pre-operative simulation improves real operative outcomes. Weston *et al.*[22] found preoperative simulation had no effect on subsequent performance. However, as discussed above, Weston *et al.* performed an *a priori* power calculation that demonstrated a larger number of participants than were actually recruited would be required to achieve the requisite statistical power and consequently, the absence of a significant result may reflect a Type II error.

5 The Characteristics of Successful Warm-Up

In order to explore the underlying mechanisms for the observed performance improvements through preoperative simulation, we performed a rudimentary analysis of the tasks performed through a dualistic framework of surgical performance- parsing cognitive and motor processes[42] (**Table 4**).

---INSERT TABLE 4 HERE---

5.1 The Warm-Up Tasks

Three mediums of simulation were employed by the included studies; in seven studies a virtual-reality simulator[25, 27–30, 33], in four a laparoscopic box trainer[21, 23, 26, 32], and in two, video-games[24, 31]. Though various forms of simulation were employed, there was a general concordance across the studies as to what constituted preoperative simulation. All studies, except one[34], used a similar or simplified motor task as preoperative simulation before performing the assessed task.

Whilst acknowledging that motor and cognitive processes do, and must, work in concert, and although necessarily speculative in nature, investigation into the degree of engagement of each system could assist with the future development of optimal preoperative simulation interventions. Thus, we categorised the preoperative simulation routines employed in each study into those more likely to engage motor or cognitive processes.

The majority of included studies[22–33] tapped into motor related tasks in their preoperative simulation routines. For example, in most of these cases, a simplified simulated task (*cf.* the assessment task) was used to prepare the participants for surgery (real-life or simulated) and thus, demanded a repetition of motor action. Two studies[27, 30] had, what appears to be a more even distribution of cognitive and motor demands in their preoperative

simulation and one study relied on cognitive alone (complete absence of motor action)[34].

One RCT[34] reported participants' mental imagery following mental practice (experimental group)- defined as "the cognitive rehearsal of a task in the absence of overt physical movement"[34]- or an online academic activity (control group) immediately prior to performing a simulated laparoscopic cholecystectomy. The authors reported undertaking structured mental practice significantly improved participants' mental imagery of a procedure. Finally, in one cross-over study[28] it was found that preoperative simulation improved attention, reduced distraction / drowsiness and reduced mental workload in comparison to no warm-up.

6 Discussion

Consistent with previous evidence on the potential value of warm-up, all but one of the studies included in this review concluded that preoperative simulation significantly improves subsequent surgical performance. Thus, it appears that surgeons may benefit from engaging in formalised preparation routines before carrying out a procedure. However, the heterogeneity of the studies identified means that there are a number of outstanding questions that must be addressed regarding how warm-up should be effectively implemented. We discuss these issues, alongside the strengths and limitations of the reviewed studies, and present perspective on future research below.

The studies reported here worked outside any obvious theoretical framework- as evidenced by the narrow focus of preparatory procedures employed. The interventions were biased towards a motoric interpretation of preoperative simulation. As outlined in the introduction, human behavior can be understood as an interaction between cognitive and motor systems. The studies reviewed here predominantly focused on more automated behaviours at the neglect of controlled cognitive processes. We speculate that interventions relying on both are likely to produce greater benefit than focusing on a single process alone[43].

We suggest that a more rigorous approach to the development and implementation of preoperative simulations is necessary. A rich history of theoretical and empirical approaches to understanding human performance exists in cognitive science[14, 42, 44–50]– employing approaches from this body of work and mapping surgical simulation to our understanding of human decision-making should help maximise the potential of this intervention.

Central to our investigation was the examination of the outcome metrics that might be influenced by warm-up. We found a high number of outcome metrics within and across the studies reviewed (see **Table 3**). Whilst this is problematic, difficulties in deducing a clear

picture from the literature are compounded by the finding that only four studies[22, 23, 29, 32] showed concordance between all reported outcome measures within the studies. Three of these studies[23, 29, 32] concluded that preoperative simulation improves surgical performance. One study[22] (45) reported that preoperative simulation does not affect subsequent performance but, as noted earlier, this study lacked sufficient statistical power. The nine other studies[24–28, 30, 31, 33] included in this review reported significant results in some, but not all, recorded outcome measures. All of these studies concluded overall that preoperative simulation improves surgical performance, but only two studies[25, 28] (48,51) include an explanation as to why significant results were prioritised over non-significant results.

The selective reporting of significant outcome measures may bias the conclusions drawn from these studies. This is an issue that generalises - a consensus opinion on outcome reporting is imperative to allow effective meta-analysis of results and permit a high quality evidence base to be developed. Surgical education and training should follow the example set by clinical research by agreeing a set of standardised outcomes to report[40, 51–53]. **Whilst a comprehensive discussion of this issue is beyond the scope of the current review, standardising outcome reporting is particularly necessary, and most amenable, in the assessment of simulated surgical skills.** Surgery performed on real patients can be assessed by reviewing patient outcomes (although none of the included studies reported such data) - the gold-standard of outcome reporting.

Simulation-based research often relies on outcomes of convenience. For example, one of the most frequently reported outcome metrics in this systematic review was performance time. While it is recognised that expert performance is faster than novice performance[10, 11], the converse is not necessarily true, i.e. faster performance does not necessarily confer better quality surgery[54, 55]. The same applies to simulator-generated metrics; for example, while experts tend to have smoother movements, having smoother movements does not necessarily mean the operator is an expert. Consequently, such

metrics, particularly when reported without additional objective or subjective data, can only be interpreted with considerable caution. Despite this, the majority of reported outcomes demonstrate that preoperative simulation does have a beneficial effect on subsequent surgical performance, in both simulated and real-patient environments.

In this review, studies were included irrespective of the type of surgical skill being examined. The heterogeneity of the included studies can be viewed as a strength of this review as the generic concept of preoperative simulation can be explored across multiple surgical specialties, using a variety of assessment methods. Conversely, the disparity between studies and the number of different outcome metrics used prevent a quantitative synthesis of reported outcomes. In addition, it is worth noting that because of the paucity of studies in the literature, designs that are often excluded from systematic reviews have been included.

Further research is clearly required in this area, but despite the limitations of the studies reviewed, the data taken as a whole indicate that preoperative simulation could prove to be a highly promising avenue for future interventions. No study demonstrated, or even implied, that preoperative simulation has a detrimental effect on subsequent surgical performance. Anecdotal evidence suggests that many surgeons currently employ some form of ad-hoc informal preoperative simulation already. The ease of implementing preoperative simulation with the potential for profound changes in patient safety leads us to identify this as a critical area for further study.

In conclusion, evidence from the literature suggests that preoperative simulation improves subsequent surgical performance, both in simulated and real-patient environments. Nevertheless, there is a need for further rigorous, empirically and theoretically driven interventions to maximise any benefit that preoperative simulation might yield. The next challenge for this field is to develop formalised, theoretically grounded, approaches that can be integrated into hospital processes to optimise the practice of surgery.

Author Disclosures

Mr. Pike, Mr. Pathak, Dr Mushtaq, Dr Wilkie, Professor Mon-Williams and Professor Lodge have no conflicts of interest or financial ties to disclose.

References

1. Catchpole K, Panesar SS, Russell J, Tang V, Hibbert P, Cleary K (2009) Surgical safety can be improved through better understanding of incidents reported to a national database.
2. White AD, Skelton M, Mushtaq F, Pike TW, Lodge JPA, Wilkie RM (2015) Inconsistent reporting of minimally invasive surgery errors. 1–5. doi: 10.1308/rcsann.2015.0038
3. Chalmers C, Joshi S, Bentley P, Boyle N (2010) The Lost Generation: Impact of the 56-hour EWTD on Current Surgical Training. *Bull R Coll Surg Engl* 92:102–106. doi: 10.1308/147363510X491105
4. Report of the Independent Working Time Regulations (2014) The Implementation of the Working Time Directive, and its Impact on the NHS and Health Professionals.
5. House of Commons Health Committee (2008) HC 25-I Modernising Medical Careers Third Report of Session 2007–08 Volume I Report, together with formal minutes.
6. Healy N, Chang K, Conneely J, Malone C, Kerin M (2013) Impact of supervised training on the acquisition of simulated laparoscopic skills. *Bull R Coll Surg Engl* 95:1–6. doi: 10.1308/003588413X13643054410340
7. Ahmed N, Devitt KS, Keshet I, Spicer J, Imrie K, Feldman L, Cools-Lartigue J, Kayssi A, Lipsman N, Elmi M, Kulkarni A V., Parshuram C, Mainprize T, Warren RJ, Fata P, Gorman MS, Feinberg S, Rutka J (2014) A Systematic Review of the Effects of Resident Duty Hour Restrictions in Surgery. *Ann Surg* 259:1041–1053. doi: 10.1097/SLA.0000000000000595
8. The Royal College of Surgeons of England (2009) Patient safety.
9. House of Commons Health Committee (2009) Patient safety: Sixth report of session 2009-09 Volume 1.
10. Sturm LP, Windsor JA, Cosman PH, Cregan P, Hewett PJ, Maddern GJ (2008) A systematic review of skills transfer after surgical simulation training. *Ann Surg* 248:166–79. doi: 10.1097/SLA.0b013e318176bf24

11. Dawe SR, Pena GN, Windsor JA, Broeders JAJL, Cregan PC, Hewett PJ, Maddern GJ (2014) Systematic review of skills transfer after surgical simulation-based training. *Br J Surg* 101:1063–76. doi: 10.1002/bjs.9482
12. Abdalla G, Moran-Atkin E, Chen G, Schweitzer MA, Magnuson TH, Steele KE (2015) The effect of warm-up on surgical performance: a systematic review. *Surg Endosc* 29:1259–1269. doi: 10.1007/s00464-014-3811-4
13. Moran-Atkin E, Abdalla G, Chen G, Magnuson TH, Lidor AO, Schweitzer MA, Steele KE (2015) Preoperative warm-up the key to improved resident technique: a randomized study. *Surg Endosc Other Interv Tech* 29:1057–1063. doi: 10.1007/s00464-014-3778-1
14. van Swieten LM, van Bergen E, Williams JHG, Wilson AD, Plumb MS, Kent SW, Mon-Williams MA (2010) A test of motor (not executive) planning in developmental coordination disorder and autism. *J Exp Psychol Hum Percept Perform* 36:493–499. doi: 10.1037/a0017177
15. Diedrichsen J, Kornysheva K (2015) Motor skill learning between selection and execution. *Trends Cogn Sci*. doi: 10.1016/j.tics.2015.02.003
16. Calhoun VD, Eichele T, Adalı T, Allen EA (2012) Decomposing the brain: components and modes, networks and nodes. *Trends Cogn Sci* 16:255–6. doi: 10.1016/j.tics.2012.03.008
17. Freedman DJ, Assad J a (2011) A proposed common neural mechanism for categorization and perceptual decisions. *Nat Neurosci* 14:143–146. doi: 10.1038/nn.2740
18. Cohen MX, Ranganath C (2005) Behavioral and neural predictors of upcoming decisions. *Cogn Affect Behav Neurosci* 5:117–126.
19. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gøtzsche PC, Ioannidis JPA, Clarke M, Devereaux PJ, Kleijnen J, Moher D (2009) The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. *BMJ* 339:
20. Higgins JPT, Altman DG, Gøtzsche PC, Jüni P, Moher D, Oxman AD, Savovic J, Schulz KF, Weeks L, Sterne JAC, Cochrane Bias Methods Group, Cochrane Statistical Methods Group (2011) The Cochrane Collaboration’s tool for assessing risk

of bias in randomised trials. *BMJ* 343:d5928.

21. Mills EJ, Chan A-W, Wu P, Vail A, Guyatt GH, Altman DG, Mills E, Kelly S, Wu P, Guyatt G, Louis T, Lavori P, Bailar J, Polansky M, Elbourne D, Altman D, Higgins J, Curtin F, Worthington H, Vail A, Maclure M, Brown B, Cleophas T, Vogel E de, Cleophas T, Daya S, Khan K, Daya S, Collins J, Walter S, Chan A, Altman D, Robinson K, Dickersin K, Altman D, Schulz K, Moher D, Egger M, Davidoff F, Elbourne D, Gøtzsche P, Lang T, Jaynes =ET, Schwartz J, Bugianesi K, Ebel D, Smet M De, Haesen R, Larson P, Powers J, Gooch W, Oddo L, Koutsoumbi P, Epanomeritakis E, Tsiaoussis J, Athanasakis H, Chrysos E, Zoras O, Vassilakis J, Xynos E, Turley E, McKeown A, Bonham M, O J, Herrera D, Mayet L, Galindo M, Jung H, Kosoglou T, Salfi M, Lim J, Batra V, Cayen M, Affrime M, Lepore M, Pampanelli S, Fanelli C, Porcellati F, Vincenzo A Di, Cordoni C, Nakaishi H, Matsumoto H, Tominaga S, Hirayama M, Marathe P, Arnold M, Meeker J, Greene D, Barbhaiya R, Marx C, McIntosh E, Wilson W, McEvoy J, Holt S, Suder A, Dronfield C, Holt C, Beasley R, Fernhall B, Szymanski L, Gorman P, Kamimori G, Kessler C, Schulz K, Chalmers I, Hayes R, Altman D, Moher D, Schulz K, Altman D, Devereaux P, Choi P, El-Dika S, Bhandari M, Montori V, Schünemann H, Wallenstein S, Fisher A, Senn S, D G, Senn S, Liu G, Liang K (2009) Design, analysis, and presentation of crossover trials. *Trials* 10:27. doi: 10.1186/1745-6215-10-27
22. Weston MK, Stephens JH, Schafer A, Hewett PJ (2012) Warm-up before laparoscopic surgery is not essential. *ANZ J Surg*. doi: 10.1111/j.1445-2197.2012.06321.x
23. Chen CCG, Green IC, Colbert-Getz JM, Steele K, Chou B, Lawson SM, Andersen DK, Satin AJ (2013) Warm-up on a simulator improves residents' performance in laparoscopic surgery: a randomized trial. *Int Urogynecol J*. doi: 10.1007/s00192-013-2066-2
24. Plerhoples T a, Zak Y, Hernandez-Boussard T, Lau J (2011) Another use of the mobile device: warm-up for laparoscopic surgery. *J Surg Res* 170:185–8. doi: 10.1016/j.jss.2011.03.015
25. Lendvay TS, Brand TC, White L, Kowalewski T, Jonnadula S, Mercer LD, Khorsand D, Andros J, Hannaford B, Satava RM (2013) Virtual reality robotic surgery warm-up improves task performance in a dry laboratory environment: a prospective randomized controlled study. *J Am Coll Surg* 216:1181–92. doi: 10.1016/j.jamcollsurg.2013.02.012

26. Kroft J, Ordon M, Arthur R, Pittini R (2012) Does surgical "warming up" improve laparoscopic simulator performance? *Simul Healthc* 7:339–42. doi: 10.1097/SIH.0b013e31826230d4
27. Willaert WIM, Aggarwal R, Daruwalla F, Van Herzeele I, Darzi AW, Vermassen FE, Cheshire NJ (2012) Simulated procedure rehearsal is more effective than a preoperative generic warm-up for endovascular procedures. *Ann Surg* 255:1184–9. doi: 10.1097/SLA.0b013e31824f9dbf
28. Lee JY, Mucksavage P, Kerbl DC, Osann KE, Winfield HN, Kahol K, McDougall EM (2012) Laparoscopic warm-up exercises improve performance of senior-level trainees during laparoscopic renal surgery. *J Endourol* 26:545–50. doi: 10.1089/end.2011.0418
29. Calatayud D, Arora S, Aggarwal R, Kruglikova I, Schulze S, Funch-Jensen P, Grantcharov T (2010) Warm-up in a virtual reality environment improves performance in the operating room. *Ann Surg* 251:1181–5. doi: 10.1097/SLA.0b013e3181deb630
30. Moldovanu R, Târcoveanu E, Dimofte G, Lupașcu C, Bradea C (2011) Preoperative warm-up using a virtual reality simulator. *JSLS* 15:533–8. doi: 10.4293/108680811X13176785204409
31. Rosser JC, Gentile DA, Hanigan K, Danner OK (2012) The effect of video game "warm-up" on performance of laparoscopic surgery tasks. *JSLS* 16:3–9. doi: 10.4293/108680812X13291597715664
32. Do AT, Cabbad MF, Kerr A, Serur E, Robertazzi RR, Stankovic MR A warm-up laparoscopic exercise improves the subsequent laparoscopic performance of Ob-Gyn residents: a low-cost laparoscopic trainer. *JSLS* 10:297–301.
33. Kahol K, Satava RM, Ferrara J, Smith ML (2009) Effect of short-term pretrial practice on surgical proficiency in simulated environments: a randomized trial of the “preoperative warm-up” effect. *J Am Coll Surg* 208:255–68. doi: 10.1016/j.jamcollsurg.2008.09.029
34. Arora S, Aggarwal R, Sirimanna P, Moran A, Grantcharov T, Kneebone R, Sevdalis N, Darzi A (2011) Mental practice enhances surgical technical skills: a randomized controlled study. *Ann Surg* 253:265–270. doi: 10.1097/SLA.0b013e318207a789
35. Derossis AM, Fried GM, Abrahamowicz M, Sigman HH, Barkun JS, Meakins JL

- (1998) Development of a Model for Training and Evaluation of Laparoscopic Skills. *Am J Surg* 175:482–487. doi: 10.1016/S0002-9610(98)00080-4
36. Van Herzeele I, Aggarwal R, Malik I, Gaines P, Hamady M, Darzi A, Cheshire N, Vermassen F (2009) Validation of Video-based Skill Assessment in Carotid Artery Stenting. *Eur J Vasc Endovasc Surg* 38:1–9. doi: 10.1016/j.ejvs.2009.03.008
 37. Martin RCG, Scoggins CR, McMasters KM (2010) Laparoscopic Hepatic Lobectomy: Advantages of a Minimally Invasive Approach. *J Am Coll Surg* 210:627–634. doi: 10.1016/j.jamcollsurg.2009.12.022
 38. Kundhal PS, Grantcharov TP (2009) Psychomotor performance measured in a virtual environment correlates with technical skills in the operating room. *Surg Endosc* 23:645–649. doi: 10.1007/s00464-008-0043-5
 39. Vassiliou MC, Feldman LS, Andrew CG, Bergman S, Leffondré K, Stanbridge D, Fried GM (2005) A global assessment tool for evaluation of intraoperative laparoscopic skills. *Am J Surg* 190:107–113. doi: 10.1016/j.amjsurg.2005.04.004
 40. Blencowe NS, McNair AGK, Davis CR, Brookes ST, Blazeby JM (2012) Standards of Outcome Reporting in Surgical Oncology: A Case Study in Esophageal Cancer. *Ann Surg Oncol* 19:4012–4018. doi: 10.1245/s10434-012-2497-x
 41. Reznick RK (1993) Teaching and testing technical skills. *Am J Surg* 165:358–361. doi: 10.1016/S0002-9610(05)80843-8
 42. Kahneman D, Tversky A (1979) Prospect theory: an analysis of decision under risk. *Econometrica* 47:263.
 43. Allen RJ, Waterman AH (2014) How does enactment affect the ability to follow instructions in working memory? *Mem Cognit*. doi: 10.3758/s13421-014-0481-3
 44. Körding KP, Wolpert DM, Kording KP (2006) Bayesian decision theory in sensorimotor control. *Trends Cogn Sci* 10:319–26. doi: 10.1016/j.tics.2006.05.003
 45. Friston KJ, Daunizeau J, Kilner J, Kiebel SJ, Friston KJ, Daunizeau J, Kilner J, Kiebel SJ Action and behavior: a free-energy formulation. doi: 10.1007/s00422-010-0364-z
 46. Reyna VF, Estrada SM, DeMarinis JA, Myers RM, Stanisiz JM, Mills BA (2011) Neurobiological and memory models of risky decision making in adolescents versus young adults. *J Exp Psychol Learn Mem Cogn* 37:1125–42. doi: 10.1037/a0023943

47. Wang X-J (2008) Decision making in recurrent neuronal circuits. *Neuron* 60:215–34. doi: 10.1016/j.neuron.2008.09.034
48. Starcke K, Brand M (2012) Decision making under stress: a selective review. *Neurosci Biobehav Rev* 36:1228–48. doi: 10.1016/j.neubiorev.2012.02.003
49. Sanfey AG, Chang LJ (2008) Multiple systems in decision making. *Ann N Y Acad Sci* 1128:53–62. doi: 10.1196/annals.1399.007
50. Rangel A, Camerer C, Montague PR (2008) A framework for studying the neurobiology of value-based decision making. *Nat Rev Neurosci* 9:545–56. doi: 10.1038/nrn2357
51. Whistance RN, Forsythe RO, McNair AGK, Brookes ST, Avery KNL, Pullyblank AM, Sylvester PA, Jayne DG, Jones JE, Brown J, Coleman MG, Dutton SJ, Hackett R, Huxtable R, Kennedy RH, Morton D, Oliver A, Russell A, Thomas MG, Blazeby JM, Core Outcomes and iNformation SEts iN SURgical Studies - ColoRectal Cancer Working Group (2013) A systematic review of outcome reporting in colorectal cancer surgery. *Colorectal Dis* 15:e548–60. doi: 10.1111/codi.12378
52. Macefield RC, Boulind CE, Blazeby JM (2014) Selecting and measuring optimal outcomes for randomised controlled trials in surgery. *Langenbeck's Arch Surg* 399:263–272. doi: 10.1007/s00423-013-1136-8
53. Gargon E, Gurung B, Medley N, Altman DG, Blazeby JM, Clarke M, Williamson PR, Chalmers I, Glasziou P, Hirsch B, Califf R, Cheng S, Tasneem A, Horton J, Kirkham J, Gargon E, Clarke M, Williamson P, Miyar J, Adams C, Dwan K, Altman D, Arnaiz J, Bloom J, Chan A-W, Williamson P, Altman D, Blazeby J, Clarke M, Devane D, Sinha I, Jones L, Smyth R, Williamson P, Moher D, Liberati A, Tetzlaff J, Altman D, Group P, Chan A, Tetzlaff J, Gotzsche P, Altman D, Mann H, Moher D, Schulz K, Simera I, Altman D, Kostanjsek N (2014) Choosing Important Health Outcomes for Comparative Effectiveness Research: A Systematic Review. *PLoS One* 9:e99111. doi: 10.1371/journal.pone.0099111
54. Al-Saud LM, Mushtaq F, Allsop MJ, Culmer PC, Mirghani I, Yates E, Keeling A, Mon-Williams MA, Manogue M (2016) Feedback and motor skill acquisition using a haptic dental simulator. *Eur J Dent Educ* 1–8. doi: 10.1111/eje.12214
55. Mirghani I, Mushtaq F, Allsop M, Potter C, Tickhill N, Al-Saud LMS, Keeling A, Mon-Williams M, Manogue M (2016) Capturing differences in dental training using a virtual

reality simulator. (Accepted pending minor revisions). Eur. J. Dent. Educ.

Table Legends

Table 1A - Risk of bias table for Plerhoples *et al.*

Table 1B - Risk of bias table for Weston *et al.*

Table 1C - Risk of bias table for Chen *et al.*

Table 1D - Risk of bias table for Lendvay *et al.*

Table 1E – Risk of bias table for Arora *et al.*

Table 1F - Risk of bias summary table for included RCTs

Table 2 - Risk of bias table for included cross-over trials

Table 3 - Outcome measures reported by included studies

Table 4 – Summary of the underlying cognitive processes examined by the included studies