Virtual Suturing for Training in Vascular Surgery

by

Richard Paul Holbrey

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Abstract

Today's health professionals are facing a crisis in training needs: on one hand, the working hours of junior doctors and experience at the operating table are being reduced; on the other, patients are growing ever more critical and litigious. VR simulators may be able to provide a solution, but whilst hardware costs have fallen in recent years, they are still expensive when compared to conventional methods and few have been adopted. The challenge for researchers has been to create realistic, but affordable, surgical interfaces and to provide convincing assessments of the resulting systems.

There are several common forms of assessment in the surgical simulation literature. The most popular would seem to be the *construct validity* test, in which experts' performance is contrasted with that of novices. Although this method provides a useful check, it is argued that the results are often unreliable, given the short-term nature of the test and the difficulty of separating practice and learning effects. Moreover, a wider literature search shows that consistency and persistency of performance are much more highly respected in eg. military and aviation contexts.

A design for a virtual suturing simulator, dubbed *FESTIVALS*, is proposed which is based upon principles established in motor psychology over the last few decades. In particular, practice variability is promoted by requiring the user to employ both hands in facilitating access. Also, a delayed feedback schedule is introduced to provide feedback on errors.

The Finite Element Method is adapted to build an accurate deformation model to support bimanual working and real-time haptic display. Evaluation of this system showed that the *FESTIVALS* system possessed good training and retention characteristics. In addition, a usability study collected feedback from clinicians which showed a generally favourable response and allowed several recommendations for future development.

By considering discrete phases of the suturing data collected in these evaluations, it is also possible to show that *construct validity* held for several metrics. This is of particular interest because it appears to show that experts were much more capable of planning specific movements in advance, suggesting a more highly developed technique for error-control. This finding led to a novel proposal for an error-correction model of expertise.

Acknowledgements

As a cross-disciplinary exercise, it was often difficult to give an appropriate framework for progress in this project. That any was made is due to the supervision of Ken Brodlie and Andy Bulpitt. Mark Walkley contributed vital Finite Element guidance. Jason Wood and Ian Eastwood helped with the needle driver switch (and other electronics). Julian Scott, David Kessel and Kevin Mercer (of St James' Hospital, Leeds) and Mark Lansdown (of LIMIT, Leeds General Infirmary) provided crucial medical input.

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Many thanks to Ms Austen, Mr Atkinson, Ray Carver, Charles Dickens and George Orwell for light relief.

Declarations

Some parts of the work presented in this thesis have been published in the following articles: Holbrey *et al* [209] and Holbrey and Bulpitt [210].

Contributions

(1) Review: This document gives a detailed review of the literature on the development and validation of surgical simulators and contrasts this with relevant work in motor psychology and aviation. It is noted that researchers in these various fields have tended to adopt very different aproaches, which have rarely been successfully combined. In particular, there is a bias in the surgical simulation literature towards tests which aim to discriminate between expert and novice users (the *construct validity* test). It is argued that the failure to consider wider research issues has serious implications for the reliability of these tests and, consequently, for the prediction of future performance. A number of alternative strategies are suggested.

(2) Design: A design for a suturing simulator (*FESTIVALS*) is developed which draws from the findings of the review. The intention is to create a rich working environment, simulating the handling of the needle and tissue and providing effective feedback on performance. To give a realistic tissue deformation model in conjuntion with two-handed working, the method of solving finite element problems by condensation is extended (*'supercondensation'*) and a novel, parallelised scheme of collision detection and event handling is introduced.

(3) Evaluation: In a series of pilot studies, the *FESTIVALS* system is shown to be capable of promoting a high level of performance which is both consistent and persistent (ie. reliable). A usability study indicates that surgical professionals approve of the system, but some aspects of the interface need to be improved. Analysis of their data indicates that *construct validity* may be more meaningfully tested by examining errors at the level of the sub-task. In particular, consultant surgeons were observed to be much more controlled in their planning and execution of needle insertion movements.

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Chapter 1

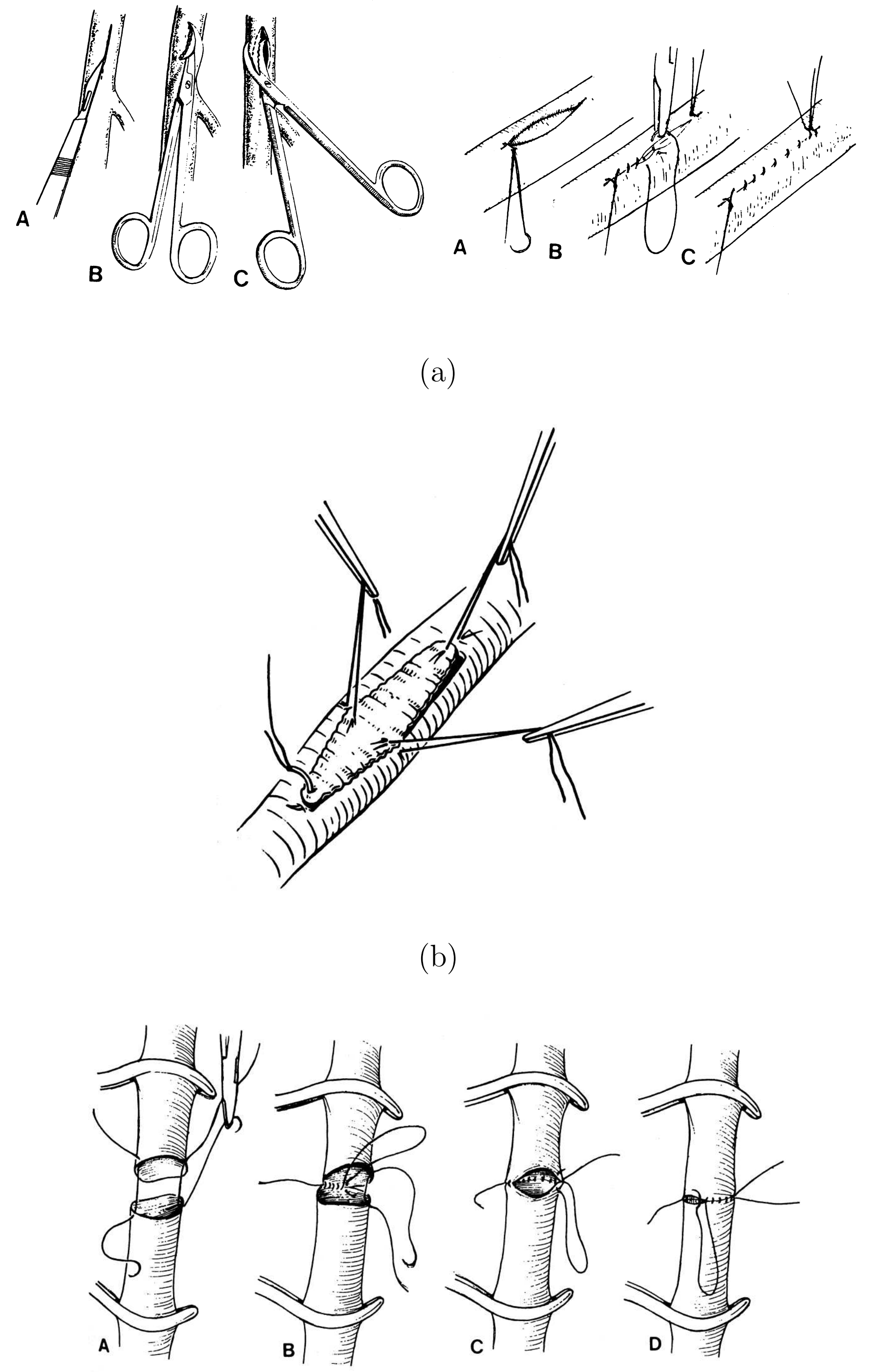
Introduction

This chapter introduces the issues surrounding surgical training apprenticeships which form the main motivation for the present research. The objectives of the current project and a research hypothesis are then formulated.

> 'Senior House Officers have been left behind. They have not benefited from the reforms enjoyed by trainees in other training grades. As a group they have been described as the workhorses of the NHS (implying a disproportionate amount of service work compared to training) and a *lost tribe* (suggesting a lack of coherence in the organisation of training).'
>
> - Liam Donaldson, Chief Medical Officer (UK), *Unfinished business...*, 2003 [139]

1.1 Motivation

Vascular surgery is a technically demanding surgical speciality, one component of which is the accurate placement of sutures through a diseased vessel wall (see Figure 1.1). As minor errors can result in thrombosis or failure of the procedure, developing the necessary skills takes many hours of practice. To date, these skills have been acquired at the operating table through serving traditional (Halsteadian) apprenticeships of 14 years or more. This period of service has changed little, until



(a)

(b)

(c)

Figure 1.1: Vascular surgical procedures

(a) longitudinal arteriotomy, (b) patch graft and (c) end-to-end anastomosis (from [191]) recently, despite the recommendations of Calman in 1993 [23] to reduce this period substantially by more specific approaches to training [194].

Qualified medical students move on to the Senior House Officer (SHO) grade after completing medical school and spending a year as pre-registration house officers. They then opt to become either a specialist registrar (SpR) or GP registrar. Nearly half of all doctors in training in the United Kingdom are at the SHO grade — currently a figure of almost 20,000 people, a third of whom are non-UK graduates — and many of these are being asked to act as registrars, without appropriate qualifications [263]. The Chief Medical Officer for the UK, Liam Donaldson, recently observed that the training programme for SHOs remains particularly weak:-

- About half of all SHO posts are free-standing and do not form part of any training rotation or programme;
- Many SHOs receive limited career guidance and are left to decide on and to follow their own career pathways in the hope that their choice of posts will support their final career choice;
- Even where posts have been grouped to form a rotation this does not usually meet the requirements of a managed programme of training;
- The quality of training can be indifferent;
- The constant need to secure short-term posts means frequent job applications and participation in appointments committees which creates uncertainty for trainees and is an added burden for the service .

To bring apprenticeships in line with Calman, operative exposure for junior surgeons has now been effectively halved. In addition, Donaldson has recommended that, from 2005, newly qualified doctors will enter a 2-year Foundation programme, after which trainees must then choose their intended career, prior to entering a further 6-year programme [139]. For training and assessment, the medical profession has long accepted the need to exploit substitutes such as cadaveric, animal and synthetic tissues. Besides legal and ethical concerns, however, a major criticism is the lack of fidelity of these materials to represent particular human anatomy and disease [107, 183, 221, 465]. The assessment of students at the Foundation stage and the problem of providing more realistic models for training are important areas which have yet to be fully addressed [259, 428, 442].

By contrast, the use of training simulations in aviation (and other high profile industries) has reached an extraordinary degree of sophistication. Static, desk-based simulators were originally introduced into training programmes during the Second World War to teach instrument displays and controls and this is still an important function of many PC-based flight simulator systems. Today, however, several bodies exist to oversee the quality of commercial flight simulators and it is now common for simulator prototypes to be constructed well in advance of genuine aircraft. Prototypes will be developed and tested for hundreds of ‘flights’ in this stage, providing important feedback to the design process [284].

1.2 Research challenges

The first surgical simulators appeared in the early 1980s, comprising video and electromechanical devices, such as [353]. Over the last decade, the success of VR trainers in other domains, and the falling costs of hardware have prompted a much more sustained research effort [398]. The development of *Minimally Invasive Surgery* (MIS) or ‘keyhole surgery’ during the early 1990s provided a powerful fillip and several commercial simulator systems are now available for MIS procedures eg. KISMET [242].

For the simulation of open surgical procedures, a number of significant research problems remain:-

- Hardware issues:

  Haptic (force display) devices must allow appropriate movements to be represented and constrained.

  Stereo graphics can give some sense of depth, but it is not clear if this is sufficient.

- Deformable modelling:

  Realistic tissue models require complex mathematics, but haptic displays require update rates of *c.*1000Hz. The situation dictates that a balance between realism and computational load must be found. The resulting models have tended to give unrealistic feedback, or allow only limited involvement in the virtual scene [131, 336].

  Most collision detection libraries are optimised for use with rigid bodies, and are, therefore, not suited to use with deformable models.

- Validation:

  Despite the adoption of a number of techniques from psychometric testing, this area remains crucially difficult. Teaching universities and departments may be ideal testing grounds, but the initial cost and maintenance of VR systems is usually too prohibitive for them to consider buying into such technology. This is particularly unfortunate as the system developers then lack vital feedback. Consequently, VR tools must somehow offer better defined trainee assessments, developed along with the system [108].

1.3 Bench models in surgical training

A recent trend in the UK and elsewhere is to require surgical trainees to undertake a Basic Surgical Skills course early in their apprenticeship. The course makes use of a number of bench models and prosthetic devices but for training in vascular surgery, a small jig is used to mount segments of pig aorta (*ex vivo*) as synthetic substitutes are not thought to be adequate [350].

The suturing task requires the placement of sutures both to the inside and outside of the vessel which requires both hands to manipulate and steady the tissue. The subordinate hand is then used mainly to facilitate access, which has to be sufficient to allow perpendicular entry of a curved needle and for rotation of the hand so that the needle is kept moving smoothly. Of particular concern is the need to reduce stress at the edge of the wound, so that in real surgeries, for example, a patch may be used to prevent the need to draw the sides of the incision together, Figure 1.1(b). Mishandling of the needle, or harsh pulls on the suture thread, can easily cause tearing along this edge and failure of the procedure (ie. *patency* or healing will not be achieved).

1.4 Objectives

1.4.1 Modelling

Vascular surgery requires careful manipulation of tissues with both hands to judge the correct use of sufficient force. The Finite Element Method (FEM) is found to provide the best currently available model for realistic deformations and forces, but requires a pre-computation step to obtain satisfactory haptic performance. We develop the technique of condensation to allow efficient storage and recall for working with numerous contact points, large-scale deformations and the safe computation of forces. Exploration of this approach allowed a further extension to approximate the viscoelastic response of tissues, and a qualification of this model is in Chapter 6.

Using these techniques, the topology of the FE model is fixed at the outset. To represent tissue manipulation, therefore, separate roles for the deformation model, collision detection and graphical display algorithms were defined, leading to the formation of a layered design which was capable of parallelisation (described in Chapter 5]).

1.4.2 Validation

The assessments given by the best available simulators are examined in Chapter 2. A common approach is that of *construct validity* testing, in which trials on the simulator are undertaken to discriminate experts from novices (a glossary of terms is given in Appendix A.1). Whilst providing some useful information, it is often the case that learning and practice effects undermine the test fairly quickly ie. the test lacks reliability. Also, since the test has a restricted set of possible outcomes — and we expect experts to give better performances — it is argued that the data generated do little to feed back into the system for future enhancement, even if the result is positive. The measurement of retention and transfer of skills accumulated at the simulator may be far more valuable in both these respects.

1.4.3 Research hypothesis

In view of the above comments (1.4.2), the following hypothesis is advanced:

> Training using a virtual suturing simulator can improve real-world performance.

In particular, we wish to assess whether skills measured and acquired at the simulator might realistically be transferred to the operating theatre.

1.4.4 Layout of this report

Chapter 2 examines the way that surgical simulators have developed over the past few decades and the roles that they are expected to fulfil. Although this progress has been substantial, there are still many research challenges and very few systems have been adopted by the medical community. In Chapter 3, therefore, the adoption of simulators in other industries is reviewed and a brief survey of relevant motor psychology literature is given. Chapter 4 describes developments in soft tissue modelling and haptic interaction that have helped to bring a stronger sense of realism or *immersion* into virtual environments.

In Chapter 5, this material is drawn together to provide a design for a virtual suturing system which allows flexibility for one or two-handed use with feedback after a series of virtual ‘stitches’ are performed. The implementation of this design is discussed in terms of the performance feedback model (Chapter 5) and the deformable graphic and force-feedback modelling (Chapter 6). An evaluation of the resulting system, dubbed *FESTIVALS*, is given in Chapter 7, the results of which are discussed in Chapter 8.

Chapter 2

The Role of Surgical Simulators

In the past, surgeons have been trained through traditional apprenticeships with practice, almost exclusively, upon real patients. This chapter describes the motivation for new approaches and reviews efforts by researchers to meet these objectives. One stumbling block is the need to define appropriate metrics for assessment (Section 2.2). For simulator researchers, a further challenge is to develop interfaces which are able to represent different areas of surgery with sufficient realism (2.3 and 2.4). The evaluation of various metrics and simulators is discussed in detail throughout this chapter and a preliminary synthesis is given in Section 2.5.

> ‘Often I would have to leave my patient in theatre with a trainee anaesthetist while I went to the CICU to assess patients’
>
> - Dr Pryn, Bristol Royal Infirmary enquiry, 2002

2.1 Why should simulators be needed?

2.1.1 A famous example

Trunkey and Botney [423] have described the career of the famous surgeon Ferdinand Sauerbruch as an illuminating example. In 1910, at the age of only 35, Sauerbruch became professor of surgery at Zurich. He took the same post at Munich in 1918 and at the prestigious Humboldt University and Berlin Charité Hospital in 1927. During this time he made many outstanding contributions in thoracic surgery, presenting papers on the removal of cardiac foreign bodies, undertaking research in nutritional problems and even developing an artificial hand. After the war, and now into his seventies, Sauerbruch continued to operate. The pathologist who examined most of his cases would never disclose how many deaths or errors occurred during this period but, after confronting the hospital administrative supervisor on one occasion, was advised that:-

> In the coming struggle of the proletariat, in the clash between socialism and capitalism, millions will lose their lives. In the face of this fact it is a trivial matter whether Sauerbruch kills a few dozen people upon his operating table. We need the name of Sauerbruch.

Although dismissed from the Charité in 1949, Sauerbruch continued to operate privately in Berlin until his death in 1951.

2.1.2 Assessment of competence

Perhaps this situation would be less likely to occur today, but medical disaster stories are plentiful [56, 273, 394, 441]. The former SHO, Jed Mercurio recently wrote:-

> As many as 70,000 people die every year as a result of doctors' mistakes... When I qualified, I soon learned that there would be times when I would be called upon to conduct procedures I had never seen, let alone practised. Airline pilots learn to fly the plane before they have to carry passengers. Due to limited training opportunities, doctors gain experience by treating patients. We are carrying passengers before we know how to fly the plane [275].

For commercial pilots, assessment of competence is certainly far more rigorous: pilots must have a first class medical certificate every 6 months; they must submit to random breathalyser and urine tests for substance abuse; they must check out in a simulator at least once a year and there are additional checkouts required by the airline carriers. Every time a pilot wishes to change to another model of aircraft, they must undergo specific training at ground schools and further rigorous testing. They must then do six to seven simulator tests and finally be checked out by an air carrier inspector. The last Federal Aviation Authority (FAA) requirement is that, without exception, they must retire at age 60. Discussing the merits of such rigorous testing, Trunkey and Botney [423] observed that:-

> At the present time, there are no simulators that could completely mimic an operation, including the technical skills required to do it, or the decision making process, or both. A substitute solution would be proctoring, and we would recommend that any surgeon proposing to do a new major operation as defined by the American Board of Surgery should be proctored for three times. Furthermore, after age 59 the surgeon should be proctored for three cases in his/her specialty area annually. If and when virtual reality simulators are developed for surgery, this could obviously be a substitute for proctoring.

It is notable that the authors would prefer to see simulators being used to indicate the need for remedial training, rather than punitively. In particular, they observe that the primary purpose of most FAA and FBI simulations is to assess competence, identify problems and provide training or refer to treatment when the condition is amenable.

2.1.3 Human factors

Aviation simulators are now built and operated routinely at the design stage of new aircraft (Section 1.1). One reason for this success is undoubtedly the nature of the technology: the engineering and manufacturing expertise already existed, and, at a cost, could be adapted to recreate relatively faithful flying experiences. Secondly, and perhaps more importantly, was the abandonment of the ‘blame culture’ in favour of a *human factors* (HF) approach [117, 186]. The HF philosophy recognizes that it is common for there to be a series of errors and events leading to a particular incident, and that in such situations there is often an unhealthy state of denial: people find it difficult to raise concerns and a *primacy effect* exists in which the first hypothesis usually takes precedence.

A ‘blame culture’ still seems to flourish in medicine [275]: the catalyst for the events surrounding the recent mistaken nephrectomy in Llanelli, Wales, was a form being filled incorrectly. This was not checked against the consent form and despite objections from a medical student in theatre (that the kidney appeared to be healthy), the surgery proceeded. The patient died five weeks after the operation; the two doctors held responsible were found guilty of serious professional misconduct and suspended for 12 months by the General Medical Council. A heavier sentence was ruled out since it was not certain that the patient died as a direct result of the mistake [66].

Coxon *et al* [117] have drawn a remarkable parallel between the Llanelli case and the Kegworth disaster of 1989, in which the left engine of an aeroplane caught fire, but the right engine was switched off due to human error (poor training and bad instrument design). In this case, several passengers and cabin crew-members noticed the mistake but were reluctant to speak out, ultimately with the loss of 47 lives. Notwithstanding the events of 9/11, training in HF is thought to have made flying some 15-20 times safer than it was 30 years ago. Nevertheless, 50% of all air incidents are still attributed to human error [49].

2.1.4 From flight simulation to surgical simulation

Minimally invasive surgery (MIS) or 'keyhole' procedures require tools which must be held in a relatively fixed position and the surgeon must operate via a conventional 2D monitor. This aspect of working allows a fixed interface to be modelled and, hence, like flight simulation, VR representations are generally straightforward to achieve (Figure 2.1 demonstrates the interface developed by Immersion). A key point to realise, however, is that, due to the fulcrum effect, the instruments appear to act in reverse. The constraints of movement combined with the loss of depth cues present

Figure 2.1: HT Medical/Immersion interface

(from [25])

the surgeon with a formidable cognitive task [391].

In the early 1990s, feeling that the advantages of MIS — shorter hospital stays and less postoperative pain — outweighed concerns about skills in spatial awareness, many surgeons hurriedly invested in new equipment. The numerous tragic cases which resulted sparked a number of animated debates [221, 224, 269, 372]. One commentator observed that the 'uncontrolled expansion of surgical endoscopic practice. . . amounted to the biggest un-audited free-for-all in the history of surgery' [122]. Simulators were quickly identified as the best solution for this new training requirement, and were expected to fulfil three separate roles [357, 355]:

- The screening of potential surgical candidates.
- Surgical training and assessment during residency.
- Re-certification of skilled surgeons and 'skills maintenance'.

Interest in screening candidates led to a number of devices which were essentially mechanical in nature, and designed purely to test dexterity or visuo-spatial ability, such as ADEPT (see 2.2). Progress in the development of VR surgical simulators for MIS procedures has been considerable and is discussed below (Section 2.3).

Although this field has attracted extensive research, the case for introducing simulators into the training curriculum along the lines of the FAA in North America (or the Joint Aviation Authority (JAA) in Europe) is far from clear [386]. Until this area of the training infrastructure can be addressed, however, it is unlikely that simulators will play a significant role in re-certification; some authors have suggested that skills maintenance may be more urgently needed [281].

2.2 Assessing skill and ability

2.2.1 Metrics for assessment

2.2.1.1 *Metrics workshop*

In 2001, a workshop to discuss "Metrics for Objective Assessment of Surgical Skills" was held in Scottsdale, Arizona. The main goals of the workshop were to 'define what is being measured' and to 'develop a taxonomy for measurement'. One of the organisers (Cuschieri) commented that:-

> Surgical competence requires selecting the right people and placing them in appropriate training/assessment programs. . . Some surgeons will immediately rise to a level of proficiency, the majority will remain in the "learning zone" for a longer time until proficiency is obtained, and a few will never attain a true level of proficiency [123]

A number of devices were introduced to aid in this endeavour, such as the Advanced Dundee Endoscopic Psychomotor Tester (ADEPT) and the Imperial College Assessment Device (ICSAD), described below (2.2.2 and 2.2.3). Opinion at the time was divided over the usefulness of these tools, but an appropriate model for their evaluation appears to have been provided by the Objective Structured Assessment of Technical Skill (OSATS) [335, 266].

2.2.1.2 *OSATS*

OSATS is a multi-station performance-based assessment of technical skill. The examination format comprises a specific checklist for each bench model task that is assessed and a further 'global' checklist to afford an overall rating for each student (see examples in Appendix B). Developed at the University of Toronto, Ontario, the initial work on OSATS was aimed at: (a) evaluating the reliability of skills assessments; and (b), formulating a methodology to compare live animal platforms to bench models. Thus the concepts of *validity* and *reliability* lie at the heart of OSATS. Five forms of validity were discussed at the Metrics Workshop: *face*, *construct*, *content*, *concurrent* and *predictive*. These terms are defined in Appendix A.1, but it is convenient to introduce the most commonly used here, since this language is unavoidable in much of the text which follows. Discussion of the issues surrounding these concepts and of the relationship between validity and reliability is withheld until Section 3.3.

2.2.1.3 *Construct and Concurrent Validity*

Validity refers to the extent to which the test is measuring what one thinks it is measuring. Several methods have been used to establish the validity of the OSATS. Firstly, the *construct validity was* assessed by comparing the scores of candidates at various levels of training experience (see Figure 2.2). Training level accounts for 40–50% of the variation in checklist and global rating scores, suggesting reasonable construct validity for both measures. Secondly, to establish the *concurrent validity*, an identical set of six stations was administered in both a bench model format and

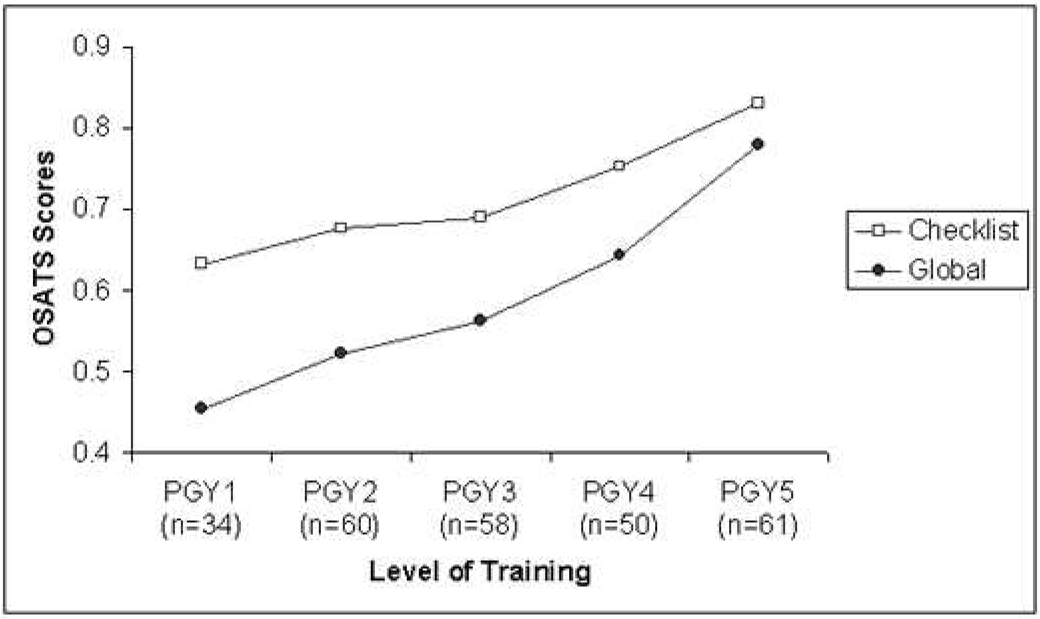


Figure 2.2: Construct validity test for OSATS

(form Regehr and Reznick [123])

in a live animal format (using pigs). The Pearson's correlation statistic between the bench and live versions of the examination was 0.69 for the checklist scores and was 0.71 for the global rating scales. This test was therefore 'concurrent' in the sense that the new test was compared favourably with the best available standard at that time.

2.2.1.4 ***Reliability***

Reliability refers to the accuracy of the scores generated by the examination and can be evaluated in several ways. *Inter-rater reliability* is obtained if we find good correspondence of scores between two independent evaluators. *Internal consistency* can be assessed by requesting that a candidate performs a number of similar tasks or repeatedly performs the same task (*test-retest reliability*).

2.2.2 Dexterity testing and ADEPT

ADEPT is a computer controlled workspace which consists of a dome with three ports: one for an endoscope and two for instruments (Figure 2.3). The target within

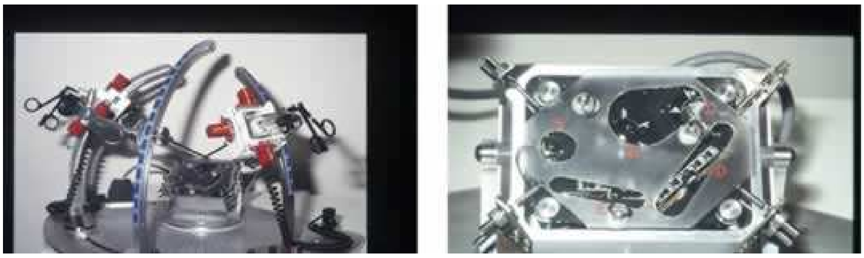


Figure 2.3: ADEPT environment

(from Cuschieri [123])

the dome is at the isocentre and viewed on a standard monitor. It comprises a plate with four tasks a flick-switch, a joystick, a rotating dial and slider tasks. Contact of the instruments with the edge of an aperture results in a 'probe error'. The software is designed to be self-running, randomly picking tasks and giving instructions.

A good correlation has been demonstrated between performance on ADEPT and independent clinical assessment of operative skills (ie. *concurrent validity*) [265]. The system appears to show a very fast learning curve, after which there is little improvement, suggesting a close correlation with individual ability rather than an acquired level of skill. Nevertheless, the authors acknowledge that testing of fundamental abilities remains a subject of much debate.

Dexterity tests have continually failed to show significant differences between clinicians of non-surgical and surgical specialities [201, 451]. A further problem is that one's abilities appear to change. Francis *et al* [160] observed that the level of eye-hand coordination of master surgeons on ADEPT was higher than that of medical students but that their capacity for novel visuo-spatial tasks was lower, suggesting that age would appear to be an important factor (see also [339, 423]). Schueneman *et al* [364] found that gender and left-handedness had a profound effect on stress levels and achievement in several tests, more so even than age.

In other concurrency tests, training effects appear to be of greater concern. Wanzel *et al* [439] examined surgical residents on a series of visuo-spatial skills, such as the mental rotation of 2D and 3D shapes, and found that those with higher scores did significantly better in performing a Z-plasty procedure for the first time. After a brief training and feedback session, however, those with lower scores were found to be indistinguishable from the highest scoring participants. Although reassuring, the authors cautioned that trainees with lesser visuo-spatial ability might need supplementary practice and feedback for each new procedure learned, whereas those with greater spatial abilities might be better able to transfer previously learned principles to new tasks. However, the authors later added that the evidence 'suggests that the learning curves are different, and that innate differences may not matter' [196].

2.2.3 Work efficiency and ICSAD

The purpose of ICSAD is to provide a more objective method of assessing skill than expert ratings or scores from devices such as the Perdue pegboard and the Minnesota small parts test, which were originally intended to test fitness for light industrial work [48]. Instead, magnetic tracking sensors are used to provide input for motion analysis of hand movements. Of the junior and senior surgeons tested in their study, the experts were found to be significantly faster to complete the tasks (suturing and knot-tying). Both groups were found to work at a similar rate, however, implying that expertise produces more economical movement (less distance travelled), rather than with higher speed (demonstrating *construct validity).*

Test results on ICSAD have also been found to correlate well with global ratings of OSATS, ie. the two systems demonstrate concurrency. Oddly, however, the results of the task-specific component of OSATS were not well correlated and did not reflect the experience of the participants. This finding appears to have been replicated by other groups, suggesting that the task-specific checklists have less reliability. Datta *et al* [126] argued that the participants all had at least two years' surgical training and were therefore all familiar with the steps of the procedure and the general principles. Furthermore, subset analyses of the task-specific checklist revealed that only 2 of the 22 elements had any bearing on the mean rank of performance (rather than all 8 parameters for the global checklist). The contrast in the sensitivity of the checklists to determine construct validity can also be seen in Figure 2.2, since the global rating shows a larger range.

Suturing and knot-tying skills examined using ICSAD are discussed in Section 2.4.4.2.

2.3 Simulation of closed procedures

2.3.1 Overview

The drive to develop simulators for MIS procedures has placed this research at the fore-front of current technology. Over a dozen studies have been undertaken using the Minimally Invasive Surgical Trainer (MIST-VR) alone. Stone [398] observed that one reason for the success of MIST was because its development was not driven by the 'technology-push' of the 1990s, which aimed:-

> to deliver comprehensive *virtual humans* using dynamic visual, tactile, auditory and even olfactory modes of interaction. . . The problem is: who in the real surgical world can afford to procure, operate and maintain such systems?

A survey of laparoscopic systems is given in Sections 2.3.2 and 2.3.3. Few of these systems include a haptic component. One exception is described by Cosman *et al* [109] who used the device to test a range of metrics (time, economy of movement, force vectors, and tissue handling) on groups of surgeons, trainees and novices. No significant differences were found, however, and no further details were given regarding the usefulness of force-feedback. In contrast, endoscopic procedures require some level of force-feedback, and for this reason, tissue modelling becomes a much more important requirement. A number of systems are discussed in Section 2.3.4. In open surgical simulations, haptic feedback is usually considered essential, and examples are discussed in Section 2.4.

2.3.2 Commercial systems

2.3.2.1 *MIST-VR*

Instead of a complex *virtual human*, the VR component of MIST comprises a number of simple objects which have to be manipulated as smoothly as possible (Figure 2.4). The system is therefore highly portable and affordable. Face and construct validity have been demonstrated by several research groups (see Appendix A.1) [387, 412]. The study by Gallagher *et al* [170], however, used a very large sample population (over 200 subjects), indicating that small differences between the novice and expert groups may easily have been exaggerated[1] [104, 297]. It is also notable

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[1] This kind of analysis has received frequent criticism from opponents of the null hypothesis significance test, who view inappropriate usage as being 'bone-headedly misguided' [296].

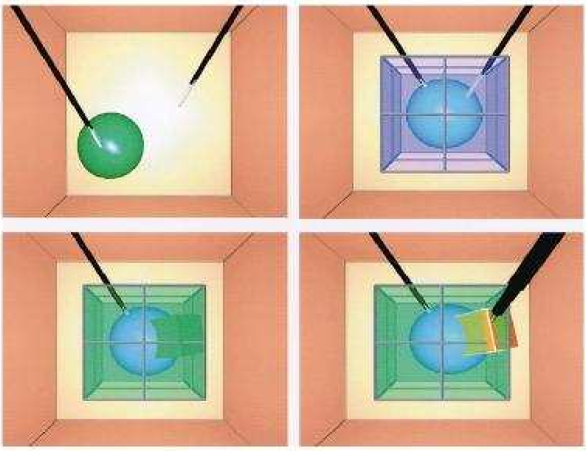

Figure 2.4: MIST-VR display

(from Gor *et al* [181])

that some expert laparoscopic surgeons performed very poorly and that many expert performances improved over the cycle of tests (significance not given). By contrast, the smaller (but more varied) study by Paisley *et al* [310], failed to find *construct validity*, the authors concluding that: ‘if simulations are to fulfil their potential then more realistic models will have to be developed that enable dissection and resection, and that reproduce problems of access.’ The authors compared a number of techniques for suturing and MIS, the results of which are discussed further and summarised in Section 2.4.4.

Seymour *et al* [375] demonstrated the *concurrent validity* of MIST with respect to laparoscopic cholecystectomy and gall-bladder excision. In this study, however, a more positive training regimen was encouraged, by allowing subjects up to eight one hour training sessions to achieve a preset criterion level of performance (set by experts). In the more restricted training regime of Ahlberg *et al* [34], novices who trained for 3 hours on MIST did no better than a control group (with no training) in the appendectomy of a pig. Although the level of training may have been insufficient here, this non-significant result is curious since other research has tended to confirm that MIST has a very quick learning curve, with a plateau being reached after at most 6 sessions [95, 181, 187].

In separate studies, Torkington *et al* have investigated the transfer and retention properties of MIST. In the transfer study [420], 30 medical students received pretests on a standard box trainer tracked by ICSAD. The participants were then divided into 3 groups: (i) control (no training); (ii) MIST-VR, completing 10 repetitions of all six training tasks twice over a period of 1 hour; and (iii) receiving standard Basic Skills instruction for 1 hour. The groups were then post-tested on the box trainer. All groups were observed to improve, though groups (ii) and (iii) improved significantly more than group (i). Basic instruction was nonetheless found to be as effective as MIST and although movement efficiency of the dominant hand was found to improve, this factor with the left hand was found to degrade. Two possible explanations were offered: firstly, that these results may represent a snapshot of the learning curve of a non-dominant hand motor skill; and secondly, that the findings may be related to the different roles performed by the two hands in the task of grasping and cutting sutures. In either case, the reliability of testing appears to be partially undermined (see 3.3).

In 2002, Mentice Corporation [12] and SimSurgery AS [17] reached an agreement for the integration of SimSurgery's simulation algorithms, including suturing, into Procedicus MIST training platform. Needle manipulation, suturing and knot-tying choreography have so far been incorporated (as yet without haptic feedback), see Figure 2.5. These features have yet to be validated as far as the author is aware but an earlier study by Kothari *et al* [241] found that training in knot-tying skills on MIST was comparable with the Yale Laparoscopic Skills Course. The basis of the assessment was the average speed of tying a knot which was observed to improve dramatically (although variances remained similar). Since no control group was employed, it is difficult to be sure about the level of progress here, but as the sessions were distributed over 5 days, this study would appear to be promoting good

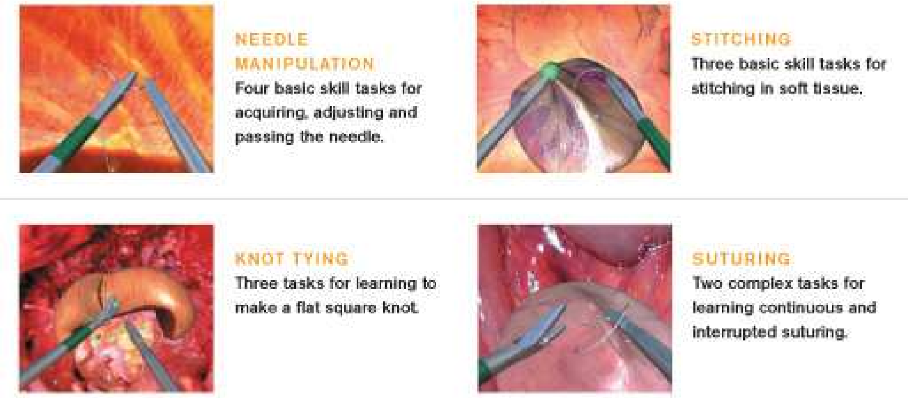

Figure 2.5: MIST suturing (from [12])

training practice (see 3.5.8).

2.3.2.2 *Wider testing of MIST*

To examine retention of skills taught elsewhere, MIST was used to assess 13 trainees before and after a Basic Skills training course [419]. The results showed that timing and efficiency metrics improved significantly by the end of course with improvements being retained at 3 weeks and 3 months as far as the logistics of the participants would allow. A control group (13 senior medical students with no prior laparoscopic experience) showed a non-significant trend toward improvement in all parameters. The accessibility of MIST has allowed researchers to investigate wider problems of sleep deprivation [411] and the effect of alcohol [237].

In a comparison study of MIST and the ratings of expert observers, Gallagher and Satava [169] obtained a good level of discrimination between groups of novices, inexperienced and experienced laparoscopic surgeons for most metrics (overall time, error and economy of movement — some differences were not apparent, however, between the inexperienced and experienced groups). The authors also made use of Cronbach's alpha (see Section 3.6.2) to give an indication of inter-rater reliability between the two observers — see Appendix A.1. A Scheffe F-test was adopted to allow family-wise comparisons (see 7.1.4).

Since operating time has frequently been held to be a distinguishing characteristic of expert surgeons, Shah *et al* supposed that reaction time might be a strongly discriminatory factor [377]. The authors concluded, however, that: 'using time as a surrogate measure for operative quality is erroneous.' An interesting departure from tests oriented purely towards skills assessment was provided by Pham *et al* [313]. In this experiment, all levels of MIST were compared with the *Rapid Fire* system (using interfaces from [21] and [25]) which was driven by a specially developed front-end, known as *Smart Tutor*. This was designed to adjust the level of feedback as users became more competent, so that only appropriate feedback was provided. Groups of medical students were trained using both systems and a pre/post-tested on a paper-cutting task. Both groups were observed to improve significantly, though the trainees found the more adaptive 'smart' system to be less frustrating[2].

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[2] Since there was no control group, the practice effect of the paper-cutting test cannot be ruled out as the cause of the improvement (see 3.6.1).

2.3.2.3 ***LapSim***

The LapSim laparoscopic trainer (Surgical Science [18]) has tasks that are more realistic than those of the MIST, involving structures that are deformable and may bleed [32]. Haptic feedback has also been added in the latest version, notably with the Basic Skills 3.0 module, which supports dissection, suturing and knot-tying. These operations are bimanual and supported by the Surgical Workstation laparoscopic interface manufactured by Immersion [25]. Figure 2.6 shows the suturing module in use. It is difficult to be more precise about the extent of this support since this is commercially sensitive information and few details have been published. The review by Schijven *et al*, however, observes that the system has a high degree of realism with regard to graphics and tissue instrument interaction but that there are no complete surgical procedures available and that validation of the system is limited but ongoing [359].

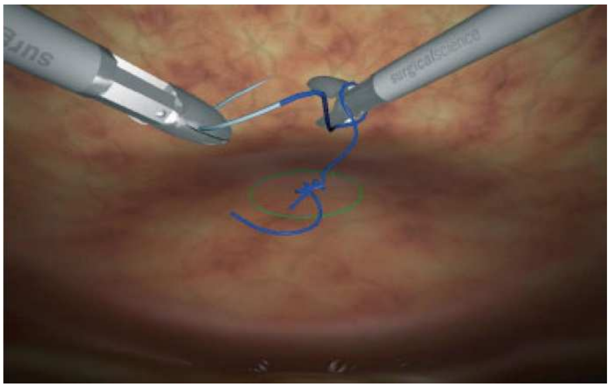

Figure 2.6: LapSim Suture module (from [32])

A number of other validation studies may be cited. Duffy *et al* [140] examined the performance of 54 surgeons (including attending surgeons and residents of all levels) over 8 training modules: camera navigation, instrument navigation, coordination, grasping, lifting and grasping, cutting, clip applying, and suturing. A summary table of significant differences obtained is given in Table 2.1, and shows a greater level of discrimination as tasks became more complex. The tasks were not repeated, so there is no assessment of the reliability of these scores (see discussion in Section 3.6.2). However, *post hoc* analysis of the most complex (suturing) task amongst residents revealed an interesting trend of development, the results of which are reproduced in Figure 2.7. There appears to be little progress until year 5 (al-

metric	Grasping	Clip application	Suturing	Knot error
Pass/Fail	*	*	*	*
Time			*	*
Level achieved	*	*	*	*
Tissue damage			*	*
Motion path		*		
Error score		*	*	*

Table 2.1: Results of Duffy *et al* [140] for contrasts between experts and novices

(* indicates significant differences)

though the variance increases markedly) and the contrast may only be significant since attending surgeons are also included[3].

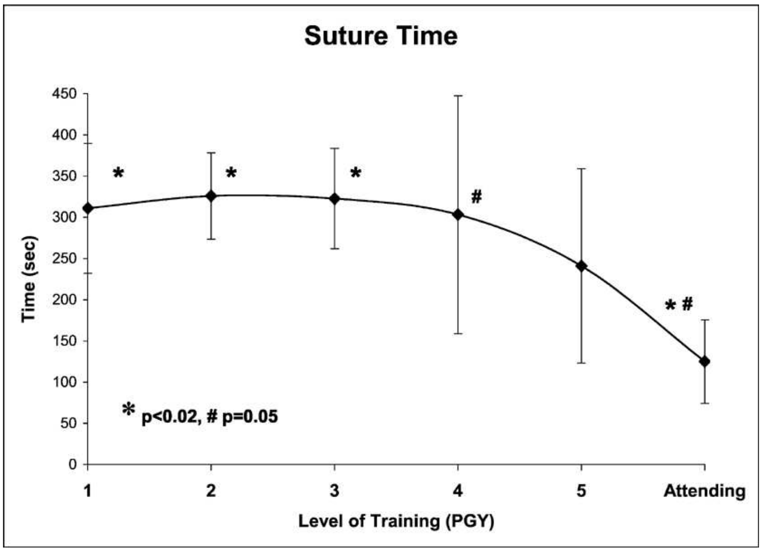

Figure 2.7: Progress in residential training (years 1–5) for suturing as evaluated by LapSim [140]

Ro *et al* have partly attributed the failure of LapSim to discriminate between intermediate level trainees to the lack of force feedback display [341]. To get a clearer understanding of training on LapSim (without haptic support), Munz *et al* [290] compared the results of a 3 week training regime (30 minute sessions each week) on LapSim and a box trainer with an untrained control group. Pre/post-assessment

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[3] Note that no form of correction was used for family-wise comparison in this ANOVA test here, although the Bonferroni procedure was adopted for multiple comparisons in earlier t-tests.

tasks were set on the box trainer, using motion analysis and error scores generated by ICSAD. Compared to the controls, the box trainer group performed significantly better on most of the parameters, whereas the LapSim group performed significantly better on some parameters. There were no significant differences between the LapSim and box trainer groups. Oddly, time taken was not significantly reduced suggesting that the performance was still improving, although the authors asserted (without further evidence) that a plateau in performance was most likely achieved after 5–6 trials (see Section 3.1.1). It is notable that the number of errors improved for all groups, including the control. Ultimately, however, the authors concluded that the study did not demonstrate any significant advantages of one modality over the other and that the effectiveness of computer-based systems was 'questionable'.

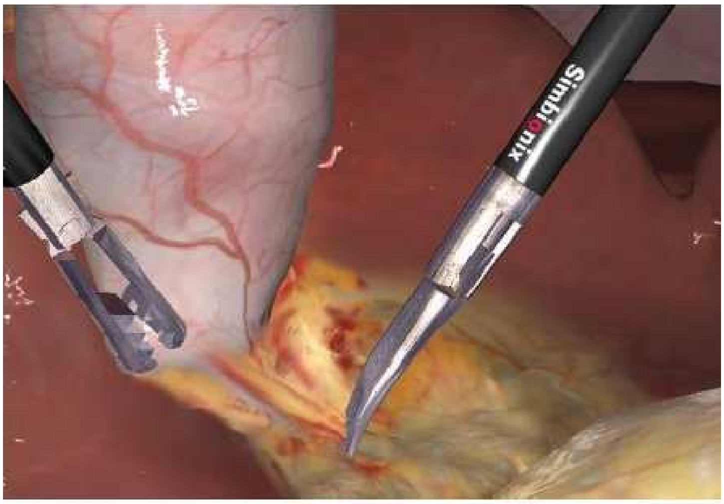
2.3.2.4 *LapMentor and ProMIS*

Aggarwal *et al* observed that LapMentor (Simbionix [16]) allows the trainee to perform a complete laparoscopic cholecystectomy and provides a force-feedback display [32]. The device employs the Xitact LS500 [22] platform for haptic sensation and provides modules for clipping, dissection and suturing, Figure 2.8. Fully published validation studies have yet to emerge, but Simbionix have published several abstracts. One study showed that the device received support from a number of trainees and had been incorporated into the curriculum at Tel Aviv Sourasky Medical Center in Israel (Szold *et al* [410]). Another compared two groups, one with 8 hours' training on the simulator and the other using normal teaching methods (observation and a box trainer). Preliminary results (unspecified) were found indicate significantly superior technical skill acquisition for the group trained on the simulator [393].

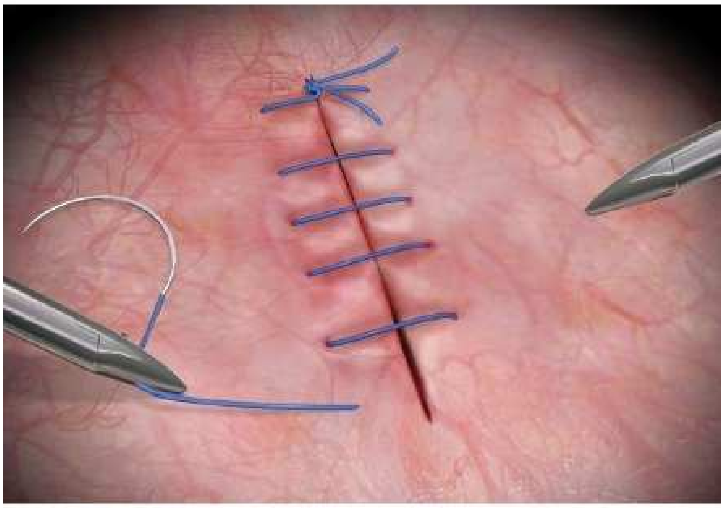
In the ProMIS environment (Haptica Inc. [8]), users interact with virtual and physical models in the same unit and the system provides facilities for instrument handling, dissection, suturing and intra-corporeal knot-tying, diathermy and ultrasonics. Trainees are tracked and provided with feedback as numeric data (time, path, 'smoothness' of movement) and graphical/video playback. The technology underpinning the device is a fusion of camera-based tracking systems, video analysis and VR. Several pilot evaluation studies have been completed:

- van Sickle *et al* demonstrated construct validity between experts and novices [432].

- Broe *et al* [76] were able to discriminate between experienced and inexperienced residents for the dissection and targeting tasks and found good inter-



Dissection and Exposure of Cystic Duct and Artery



Suturing Module - Continues Suture

Figure 2.8: LapMentor dissection and suturing (from [16] and [32])

rater correlation (using Cronbach's alpha) between blinded expert reviewers of the video playback. The authors observed that the failure of the orientation task to discriminate between groups suggested that the system required modification before it could be used in isolation as an assessment tool. It should be noted that this inference is not correct (see 3.3.2 and 3.6.2)

- Hance *et al* tested 32 subjects, comprising novices, trainees and experts, in object positioning and dissection tasks and found that significant differences existed between experts and novices, but not between experts and trainees [197].

- McCluskey *et al* undertook a study comprising 11 subjects examined over 3 trials of a suturing task on ProMIS [272]. Time, tool path and smoothness were strongly correlated, as were accuracy of suture placement and error scores (assessed by observers). Testing these correlations further, the authors found that: (i) smoothness of movement significantly correlated with accuracy in 2 trials; and (ii) time correlated well with error scores in 2 trials.

2.3.3 Inanimate trainers for laparoscopy

Testing on inanimate or box (ie. non-VR) trainers has tended to reinforce the importance of levels of experience and recent practice [133]. In fact, junior surgeons with recent practice in laparoscopy were able to out-perform their seniors who had greater experience of open surgery, but who had not practiced laparoscopic techniques for several years [157]. Regular training was found to have a dramatic effect in the study by Traxer *et al* [421]. In the control group, the time to complete a porcine nephrectomy decreased from 365 to 301 seconds on average, demonstrating a significant *practice effect* (from testing). In the trained group, practice for 30 minutes daily for 10 days produced a shift from 341 to 176 seconds (both *practice effect* and *experimental effect*). Operative assessment also improved (regardless of grouping), so that it appears that the main impact of the simulator was to improve the efficiency of working.

By evaluating hundreds of participants in Basic Skills courses with a non-VR trainer, Rosser *et al* [347, 348] were able to conclude that: 'skills relevant to laparoscopic performance can be acquired with a high level of competence in a brief course unrelated to prior surgical experience, sex, or age.' As previously, the large number of participants is a potential concern here (see above). Nevertheless, Scott *et al* [369] have produced evidence which broadly supports this conclusion using a regular training regime (30 minutes daily for 10 days) on a Stortz video-trainer. The rate of learning for second year medical students was found to be significantly greater than that of second and third year residents. (This finding may have reflected the lighter workload of medical students who may also have been more motivated by their voluntary participation.) Furthermore, in a remarkable series of studies with the same device, the authors [366, 367, 368] showed that residents' performance on human patients also improved (as assessed by supervising surgeons).

2.3.4 Endoscopy and arthroscopy

2.3.4.1 *Approaches*

Research with the angled laparoscope has shown that the learning rate is associated with visuo-spatial ability [?], but the ultimate problem of assessing a simulator by outcomes on patients may not be possible [170]. Demonstrating construct validity often seems to be given as the best possible alternative. An interesting example of the limitations of this form of testing, however, was observed with the Sheffield Knee Arthroscopy Trainer (SKAT). Construct validity was established for most tasks on SKAT, but where feedback was inappropriate — no forces were given in response to collisions — experts appeared to have no advantage [39]. Moody and Waterworth have nevertheless implemented a user-centred training tutorial, WISHKATS, based on this device [283].

Endoscopic simulators (like SKAT) have yet to be widely tested, since the modelling requirement is more demanding and has tended to dominate research [240, 242, 440], see 4 (and 3.4.3 for work on the Procedicus simulators). There are notable exceptions: controlled studies of students with the Simbionix Uromentor [443, 449] have shown significant learning effects in the trained group with respect to the control group, indicating that the required skills can be rapidly acquired by novices. A particular difficulty with training on urinary endoscopic procedures is that they are often 'one man' devices in which the teacher cannot assist the trainee directly. Brehmer and Tolley [69] compared training using a commercial bench model (from Mediskills) to checklist-scored performance with human patients. Of the 14 participants (5 trainees and 9 consultants), all found the simulator realistic to use and there was no significant discrimination between performance on the simulator and human patients. Those consultants and trainees with specific practice in advanced endourology, however, gained significantly higher scores in both tests.

2.3.4.2 *Motion analysis*

Delson *et al* [132] observed that endoscopic procedures appeared to allow multiple manipulation strategies, but that experts usually chose similar starting positions. In order to define a 'grammar' of such key points, Rosen *et al* [345] created a Markov Model (MM) of endoscopic suturing states using the Blue Dragon system [344]. Fifteen such states were identified for each hand. Testing performance of 30 trainees at various levels, the authors developed an 'objective learning curve', based on measuring quantitative statistical distance (similarity) between the MM of experts and the MM of residents at different levels, see Figure 2.9. The curve shows a pronounced plateau region between the first and final years ie. very poor discrimination.

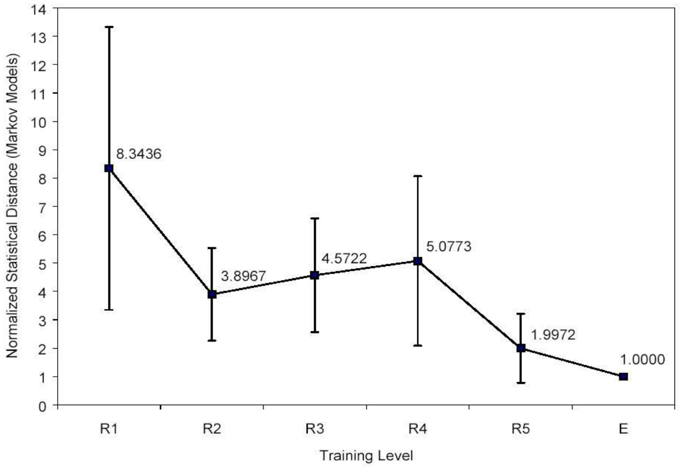


Figure 2.9: Normalised learning curve for residents

(R1-5 = residents, years 1-5, E = experts. From Rosen *et al* [345])

2.3.4.3 *Training and validity studies*

Naik *et al* compared mixed groups of first/second year trainees who were either (i) given 45 minutes' didactic instruction, or (ii) given 45 minutes practice on a simple simulator. The students were then assessed on their endoscopic technique in the 10 days after training. Simulator instruction was found to be most beneficial, the authors concluding that: 'Incorporating an extraoperative model into the training of fiberoptic orotracheal intubation may greatly reduce the time and pressures that accompany teaching this skill in the operating room' [293].

Ritter *et al* [340] observed that there is a consensus that 100–400 procedures are required to achieve competency in endoscopic procedures (see Section 3.1). Noting the earlier study by Ferlitsch *et al* [154], which demonstrated construct validity between novices and experts of more than 1000 procedures, the authors wished to test more closely matched groups. Novices (<10 procedures performed) were therefore contrasted with a group of 'intermediate' experience (100–250 procedures performed) over 3 trials using the GI Mentor II device (Simbionix [16]). An abstract VR task was selected to focus the test upon psychomotor (rather than cognitive) skills. The task, which required trainees to pop virtual balloons, was assessed by the number of balloons popped, time and collision errors (between the virtual needle and the sides of the vessel). The number of balloons popped was significantly different on all three trials, though time taken was only significantly different on the first trial and collision errors on the first and third.

The authors argued that these differences were sufficiently consistent to validate the device and pointed out that post hoc analysis (ANOVA with Dunn correction for multiple comparisons) showed significant improvement for the novices, but not for the intermediate group. Analysis also showed a good correlation between the first and second trials, indicating some degree of inter-trial reliability. The premise (validity) of this experiment is not in dispute, but there would seem to be a number of reliability issues. For example, time differences were significant on only the first trial, but this was said to demonstrate that the intermediate group was "consistently faster." Similarly, the poorer level of correlation between the second and third trials does support the authors' claim for consistency, especially for such a small number of trials. These issues are explored further in Section 3.3 (and throughout this document).

Moorthy *et al* have investigated the validity and reliability of both the GI Mentor system (Simbionix, as above) [285] and the AccuTouch Endoscopy Simulator (from Immersion Medical [10]) [286]. In the former study, the 32 participants (novices, intermediate level and experienced endoscopists) were requested to undertake two cases on the simulator, with each module being repeated twice. Metrics of performance comprised time, efficiency and several observational parameters eg. percentage of pathology seen. Also, two blinded observers rated performance after watching video playback provided by the simulator. Significant differences were seen for all metrics between the novice and experienced groups, although differences were often blurred with respect to the intermediate group. Nevertheless, the data suggested good inter-rater and inter-trial reliability, with some evidence for learning between the first and fourth trials. A questionnaire to assess the usability of the system found that endoscopists scored the simulator high on its graphics, complexity, and potential as a training tool, but that 70% of the responders rated esophageal intubation as unrealistically easy.

For the AccuTouch study, an endoscopy suite was developed along with an OSATS-style global scoring sheet (denoted as ICASE). 20 people (six experts, seven intermediate level subjects and seven novices) participated in the one test case of the suite which was recorded by ceiling-mounted cameras for external assessment (by blinded observers using ICASE). There were no significant differences across the groups in terms of the time taken for the procedure or for depth of insertion. There was, however, a significant difference across the range in terms of the percentage of time spent in 'red-out', ie. without vision, indicating that the experts were far more dexterous in their control of the device. Also, the ICASE score showed good discrimination of the three groups and good inter-rater reliability, although these scores were only well-correlated with the 'red-out' metric. One problem of studies of this kind was that the demand placed upon external observers was considerable: it was estimated that each observer spent approximately 5 hours evaluating all the simulations, which might have to be trebled with more complex procedures (eg. colonoscopy).

2.3.5 Interventional procedures

2.3.5.1 *Approaches*

A web-based catheterisation simulation has been developed by El Khalili [75, 144] which used the mouse pointer for interaction. Although it was not possible to give haptic feedback, forces were represented by a display widget. Perhaps finding such interfaces too restricting, Chong *et al* opted to create a silicone rubber phantom using a spiral Computed Tomography (CT) scan of an aortic aneurysm [99, 100]. The aortic model was attached to a pump to allow coloured dye to circulate for the simulation of arteriography and the illusion of an X-ray image was produced by placing a real X-ray on top of the apparatus. This system does not seem to have been tested or developed further: *in vitro* systems have high initial costs and limited lifetimes since they cannot be altered later to allow different anatomy or patient-specific rehearsal [184].

Nevertheless, several commercial systems have been developed and various deformable modelling methodologies have been advanced (eg. [59, 178, 330, 466]). The

Vascular Interventional Surgical Trainer (VIST; from Mentice [12]), for example, provides a complete cardiovascular system with a haptic interface, an instructional system (first monitor) and a synthetic x-ray system (second monitor), Figure 2.10.

Figure 2.10: VIST simulator (Mentice [12])

VIST is capable of simulating haemodynamics, dye contrast media mixing and interaction of the catheter. Coronary stenting can also be practiced as well as placing leads for pacing. Although promising, few of these systems have been validated to acceptable psychometric and scientific standards [93, 168, 452]. A number of completed studies are reviewed below.

2.3.5.2 *Training and validity studies*

Prystowsky *et al* [321] have tested a prototype VR device developed by jointly Musculo-Graphics Inc. and Boston Dynamics Inc. This system allowed stereo graphics and haptic feedback via a PHANToM Desktop device. In the study, 37 first-year medical students, 14 third year medical students and 9 surgical residents participated. In the pre-test and post-test, each participant attempted to perform 2 intravenous (IV) insertions on other subjects within the experiment. The treatment phase comprised orientation and ‘training’ for 12 minutes in the VR module and ratings were compiled by experts on a four-point Likert scale.

In the pre-test, there were significant differences among the groups with respect to IV insertions but none were seen amongst the groups as assessed by VR module. The rate of improvement was also similar for each group, indicating that the participants had equal difficulty becoming accustomed to the VR environment. Despite achieving a VR success rate of approximately 50% in their last 4 minutes of VR use, the first-year students' post-test success rate returned to 24%, which was similar to their pre-test success rate. The authors concluded that most groups were still in the process of learning the VR task at the end of the training period. Intriguingly they did not feel that IV insertions on other members of the group might have been detrimental to the study.

Given the poor findings of this study, Reznek *et al* [334] used a more open study design, involving usability and validity, to test CathSim ([24]). From a literature search, it was estimated that the learning curve would level at around 10 procedures, allowing subjects to be allocated as: (i) novices, with no prior experience; (ii) residents (up to 10 procedures); and (iii) attending physicians (more than 10 procedures). The results of a test comprising 5 attempted IV insertions were found to support *construct validity* for 5 of the 9 parameters obtained from the system, at least between the expert and novice groups. Of the failing parameters, one (*frequency of success*) appeared to be due to poor instruction of the participants and two more (*frequency of hematoma* and *number of recannulations*) were generally related to experience, though non-significant. It is notable that the intermediate level group was often indistinguishable from the experts (except for *average time for tourniquet application*) and, on some parameters, performance was markedly worse than both the other groups (eg. *total number of needle recannulations* and *number of incorrect tools selected*; significance not given). From questionnaires, it was felt that the realism of haptic feedback was above the average expected, but respondents also felt that the system was quite difficult to learn.

2.3.6 Robotic assistance and augmented reality

Several systems have been developed to provide robotic assistance in MIS procedures, notably daVinci and Zeus. Prasad *et al* [320] have shown that compared with performance on a standard laparoscopic trainer, robotic assistance allows for increasing speed and consistency while maintaining precision over multiple repetitions. The learning curve for using daVinci, which allows a magnified three-dimensional videoscopic view of the operative field, has been examined by [199]. Verner *et al* [433] used daVinci to track the 'flight path' of various simulator drills with distinction between experts and novices. Their intention, however, is to create reference criteria for an ideal path, against which all trainees might be measured.

An interesting departure from devices which are intended purely for training and assessment is the possibility of providing assistance during procedures by overlaying information about the patient on the surgeon's visual field [29]. The application areas for this technology include biopsy [165] and laparoscopic surgery [392]. Few studies have been completed to show the viability of this technology, although King *et al* were able to claim a 1mm focal plane accuracy for their stereo augmented microscope [234].

2.4 Simulation of open surgery

2.4.1 Overview

The difficulty of producing satisfactory VR representations of anatomy and tool/hand interaction in open surgical contexts has forced researchers to adopt a 'part-task' approach, rather than the *virtual human* systems predicted by [205, 124] and others (cf 2.3). Instead, prototype simulators have been developed in many different areas: dentistry [417], anaesthesia [292, 446], facial reconstruction [229, 230], eye [349, 351, 360] and heart [294] surgery; and for various techniques, eg. bone-dissection [33], suturing [58, 79, 209, 444] and knot-tying [314]. The validity of the part-task approach is discussed in Section 3.5.11.

In terms of completed studies, however, the literature is not vast, the bulk of research being concentrated upon deformation modelling and the physical interface, ie. software and hardware. The importance of haptic feedback for surgeons has been stressed by many authors (eg. [82]), but the problem of finding appropriate physical interfaces (which may not exist) and the solutions imposed will form a recurrent theme throughout the remainder of this thesis. This section focuses upon the results of various prototypes and trials: tissue modelling requirements and potential solutions are discussed in Chapter 4.

2.4.2 Tissue manipulation

2.4.2.1 *Background*

VR researchers face considerable difficulties in trying to provide convincing representations of tissue manipulation, since forces may be acting simultaneously from different points of origin. An early system of this type, developed by d'Aulignac *et al* [127], was intended to train the recognition of thromboses at depth within tissue.

A non-linear spring model was imported (using a commercial library) to provide force-feedback, initially fed back to the user by a PHANToM haptic device using a local interpolation scheme to provide the necessary update rate. This system does not seem to have been tested further. The (partial) validation of two haptic systems is discussed here: a veterinary device to assist with teaching students how to perform internal examinations, and a cardiac palpation simulator.

2.4.2.2 *The Horse Ovary Palpation Simulator (HOPS)*

In order to ascertain an appropriate haptic device, Crossan [118, 120, 119] reviewed a number of force-feedback tools according to principles of Lederman and Klatzky's *exploratory procedures* [246]. Despite the requirement for palpation of tissues indicating a need to enclose the hand, glove-based devices such as the Rutgers Hand Master II [150] were rejected due to the lack of lateral feedback. The PHANToM from SensAble [373] with a one-fingered gimbal end-point was preferred.

The GHOST toolkit, also from [373], was used to generate a number of rigid models with differing tactile surfaces. GHOST allows a global spring parameter to be set which can give an impression of 'softness'. This does not provide a deformable model in the true sense, but there was no need for graphical representation since the veterinary surgeon is not able to see the uterus during examination. A *construct validity* test did not reveal any significant differences between experts and novices (veterinary students). The latter, however, appeared to adopt a more game-like strategy which would not have been possible in real examinations. Both groups reported finding the exercise very difficult, and it seems likely that the interface itself played a part in these results.

In a further test (*concurrent validity*), comparisons were drawn against a group of medical students trained using traditional models and a second group trained using HOPS. Trainees were then assessed using bovine specimens. No significant effects were observed in either the concurrency test or correlations between scores on HOPS and the bovine specimens.

Crossan observed that one limitation of testing the *construct validity* of a simulator is that it does not examine the training effects of the simulator. To evaluate training effects, a repeated measures ANOVA design was used to track improvements over four training sessions of eight students, with a fifth session after one month to test retention. Performance (in terms of the number of follicles identified) improved and time decreased over the first four sessions, showing a significant training effect. Also, the last session did not show any noticeable decrease in performance, indicating the retention of skills acquired.

In conclusion, Crossan observed that a significant omission from HOPS was the ability to hold the tissue, as say, between the thumb and forefinger. A pilot study using two PHANToMs had failed, however, in that it had not proved possible to calibrate the instruments sufficiently well to use them together. It is equally likely, in the present author's opinion, that the lack of an appropriate deformable model would have contributed towards this problem.

2.4.2.3 *Cardiac Surgery*

Inanimate trainers have been used successfully within cardiothoracic training for many years, with an entire curriculum being built around some devices [182]. To simulate surgery, however, a greater level of interaction is required. Nakao [294] employed several sophisticated soft tissue models to develop a cardiac palpation simulator, with the objective of teaching trainees how to assess sclerotic tissue during open surgery. Several models were required to support different steps in the procedure. A particle-based model was employed to represent the chest wall to support cutting, using a minimal tetrahedral subdivision algorithm. Using this topological configuration, a finite element model (FEM) was computed (on-line) to allow more accurate modelling of the opening of the chest cavity. The heart itself comprised two models: the first using a FEM to allow modelling of normal/sclerotic tissue; and the second, based on the 'Long Element Method' of [110] to provide a 'heartbeat'. The haptic representation of grasping or rather, pinching, the tissue was provided by linking two PHANToMs together as Figure 2.11.

Evaluation of the model was provided by 8 cardiac surgeons who provided a subjective assessment of the model for normal and sclerotic tissue. Normal stiffness (Young's Modulus) was rated at between of 1.0–1.2 MPa, sclerotic models between 2.8–3.4 MPa. A later test assessed the ability of 18 medical students trained either with: (i) no training (control); (ii) verbal information from surgeons expressing stiffness of normal aortas using rubber hose; or (iii) with the cardiac simulator (1.0 MPa model). The results were not supported statistically, but at least graphically, appeared to favour the simulator.

Figure 2.11: Linking of PHANToMs

(from Nakao [294])

2.4.3 Suturing simulators

2.4.3.1 *Background*

Since suturing is such a common requirement in many areas of surgery, several commercial systems now claim to support some level of training, particularly in the laparoscopic environment [243, 409, ?]. This section focuses upon a few completed studies aimed at open surgical contexts and three systems are described, beginning with the *Inwound Trainer*, an electro-mechanical device produced over twenty years ago. Although this device no longer seems to be available, the authors provided a remarkably thorough evaluation and several insights into the nature of simulator training.

2.4.3.2 *The Inwound Trainer*

The Inwound device comprised a control/display unit with support for an electrically activated needle-holder (otherwise identical to the normal instrument) and a simulated tissue 'circuit-pack', which could be mounted in a mannequin-type arm. The device was capable of recognising three main operational phases: *entry*, *depth* and *exit*. Salvendy and Pilitsis [353] described the main features of the Inwound device as: (a) providing separate auditory and visual feedback for each mode during task performance; (b) allowing time and error data to be collected for these modes; and (c) permitting part practice of each mode.

Thirty-six medical students (novices in suturing) participated in the study. All were initially given a conventional classroom lecture on the specific wound-closure technique through videotape. The students were then allocated to four training groups: (i) using traditional classroom methods and pigs' feet *ex vivo* (control); (ii) using simulator and knot-tying devices; (iii) viewing film of experts and other novices; and (iv), using the simulator and viewing films (ie. ii and iii). For knot-tying, the simulator-trained groups were allocated Ethicon® tying boards with an illustrated chart for guidance. All students were trained to a subjective criterion level set by the instructors in advance. Physiological stress levels were also tested during training and assessment by monitoring muscular activity, heart rate variance and skin conductance.

The students were evaluated by expert assessment of sutures placed on pigs' feet. A further test (again using pigs' feet) was undertaken 5 days after completion of the trial and the data used to compare with expert performances. This work was reportedly undertaken to produce metrics for assessment and the results of this last test were not included in the analysis. The groups trained on the simulator were found to perform significantly better than the other groups. Group (i), having previously practised in the target environment, might have been expected to have produced the higher level of performance, but in fact lagged behind groups (ii) and (iv) in terms of number of successful stitches and performance time. Group (i) was, in fact, indistinguishable from group (iii), despite requiring three times longer to complete the training (and twice as long as the simulator group).

Additional training by using video sequences did not confer any benefit in group (iv), and even appeared to depress their results in using the simulator. This discrepancy was thought to have been caused by 'motor interference', a property which more recent authors have come to find desirable (see 3.5.8), since it appears to promote skill retention. The omission of the results regarding the later test (after 5 days) is all the more unfortunate in this regard. The results of stress testing were somewhat mixed, but showed a decline of stress through practice. The simulator groups also appeared to be under slightly greater stress (not significant statistically).

Although skills retention was not tested, the authors made use of the Hammerton model [195] to assess transfer. This test uses the following simple rule:

$$\epsilon = \frac{F - PT}{F - L} \tag{2.1}$$

- where:

F = mean performance time on simulator first trial

L = mean performance time on simulator last trial

PT = mean performance time on first post-transfer trial

and transfer is zero if $\epsilon = 0$ and positive if $\epsilon > 0$.

The values reported for the simulator groups were $\epsilon = 1.34$ for group (ii) and $\epsilon = 0.73$ for group (iv). The authors concluded that these results 'should encourage the use of this device as an inexpensive and effective training instrument.' It is not clear whether any other institutions followed this recommendation, but the author is not aware of any further studies using a similar device.

2.4.3.3 *The Boston Dynamics Incorporated (BDI) Simulator*

The BDI simulator provided two PHANToM devices for bimanual interaction and allowed a standing pose by projecting the scene onto a semi-reflective mirror, see Figure 2.12. The underlying physical model is described in Section 4.7.2, but for testing purposes it should be noted that the user was placed in open access position, only one hand being tested at any one time. It does not appear that there was any mechanism to release and re-grab the needle ('the user sutures the tubes together by puncturing each tube in sequence, then pulling the suture material tight') [318].

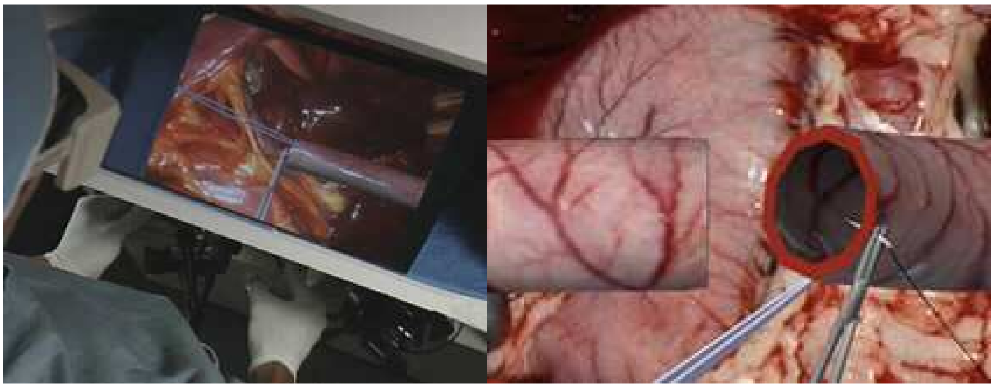


Figure 2.12: BDI Simulator

(from [52], web page and simulator now withdrawn)

In [307, 308], O'Toole *et al* proposed a number of candidate metrics for assessing vascular surgical technique. To test the (construct) validity of the metrics, an experiment was devised using 12 medical students and 8 experienced surgeons, under three conditions: (i) using the dominant hand; (ii) using the non-dominant hand; and (iii), using the dominant hand, but guided by a 3D vector which was displayed graphically. Each trial comprised four stitches and was performed in the order presented in Table 2.2. All trials were performed in one session.

Trial	Test condition
0-5	Dominant hand
6-7	Non-dominant hand
8-11	Guided by 3D vector
12-14	Dominant hand

Table 2.2: BDI study protocol

Given the seminal importance of this research towards the present study, the metrics and the results of the validity test are summarised in Table 2.3. The results show that three metrics were statistically valid discriminators between experts and trainees for both hands: *time*, *tool motion* and *tissue damage*. Since, *time* and *tool motion* have been described as providing good discrimination elsewhere (eg. for ICSAD, see 2.2.3), this result is consistent with other findings.

The significance of the 'damage' metrics is less clear, since — as the authors admitted — the name was misleading. Whereas *peak force* and *surface damage* were associated with the reaction of the model at initial contact (ie. prior to insertion), *tissue damage* was intended to assess force (above a critical threshold) away from the tangent of the needle thereafter. This was calculated by the summation of force samples, suggesting a property more closely related to *impulse* (ie. $force \times time$) than distress. In general, neither *peak force* nor *surface damage* were significantly different between the groups, but the student group took significantly longer to perform each 'suture'. It may be, therefore, that *tissue damage* was more closely related to *time* than force.

The 3D vector guide condition gave the user real-time feedback relating to the angle between the surface normal and tangent to the needle at the point of contact. The students seemed to be able to exploit this novel feature more successfully than the surgeons, since their performance with respect to the *angular error* metric was superior during these trials. Nevertheless, this 'improvement' seems to have been at the expense of a decrease in performance with respect to both 'damage' parameters (the *surface damage* metric *was* significantly different between the groups under this condition). Although the surgeons' group did not seem to be able to adapt

Metric	Description	Construct validity$^{(1)}$	Learning $^{(2)}$	Guided $^{(3)}$
Time (s)	Total time from the first contact of the vessel until the last stitch is completed	DH, NDH	E, T	E
Accuracy (m)	Distance from displayed target marker		E, T	
Peak force (N)	Largest force applied to the tissue model. A minimum as required to puncture the vessel. Increases with angular error		T	
Tissue damage (N/stitch)	Sum of force applied to the tissue in excess of a threshold (the minimum puncture force) accrued after puncturing. Increases with force components which deviate from the tangent of the needle	DH, NDH	E, T	E
Surface damage (N/stitch)	Sum of force applied to the surface of the tissue in excess of a threshold, (heavily) weighted by damage for scratches		T	E
Angular error (degrees)	The average angular difference between the needle tangent vector and the tissue's normal vector at the point of tissue contact.			T
Overall score	A weighted average of factors 1-6, normalised to 50-100%	DH	E, T	E
Tool motion (m)	Total distance that the tool tip travels. No feedback was given for this metric, and hence it was excluded from the overall score	DH, NDH	E	E

Table 2.3: BDI simulator results

(synthesised from [308])

(1) DH, NDH indicate that *construct validity* was significant for the dominant and/or non-dominant hand, respectively.

(2) E, T indicate significant improvements in the expert and trainee groups respectively. Improvements in learning were assessed using averaged data from trials 0/1 compared with trials 13/14.

(3) Under the 3D vector guided condition E or T indicates that this group performed statistically better (ie. obtained a lower error score) than the other.

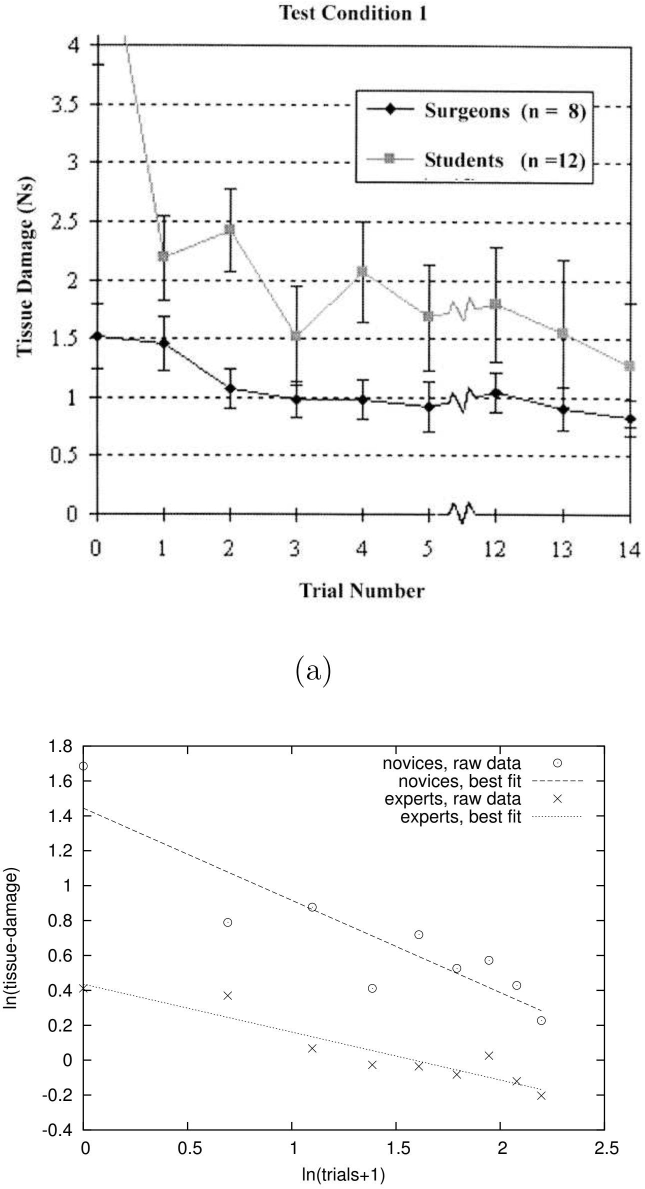
their technique, their scores for *tissue damage* would also seem to have deteriorated (significance not tested). Interestingly, these effects were not visible in earlier or later trials, indicating that these changes in behaviour were not retained (see 3.5.8).

The first and last pair of trials (dominant-handed) were used to assess possible learning effects on each metric. Both groups showed significant improvement on many of the parameters (see Table 2.3). ANOVA models of group, trial and group×trial effect also showed that student and surgeon performances changed significantly over time, although the relative level of improvement was not statistically significant between the groups. The learning curve for dominant-handed trials on the *tissue damage* metric is reproduced in Figure 2.13(a) (plotted values are mean ±1 standard error). It is notable that both groups appear to be reaching plateaux after 3 or 4 trials. Also, although both groups appear to be converging very quickly, the variance of the student group is still visibly larger.

Reznick [336] (see 2.2.1) provided an editorial on the results of these tests, noting that although the technology was moving forwards quickly, there were several possible criticisms. In particular, it was pointed out that:

1. *Reliability* and *concurrent validity* were not assessed.
2. The two groups were disparate in terms of their surgical experience and simple misconceptions (on the behalf of students) may explain the observed results.
3. The improvement of scores was perhaps more a matter of becoming used to the simulator than a matter of developing specific surgical skills.
4. Suturing was performed with a needle driver but without the aid of forceps. Many suturing tasks rely on the coordinated relationship between the movement of two hands.
5. The apparent departures from the surgical reality beg the question as to whether skills acquired in a virtual environment will be transferable to the real world of human operations.

These issues will certainly need to be addressed if more successful simulations are to be built (the development of the BDI simulator has now been suspended [R. Playter, *personal communication, July 2004*]). It is argued, however, that the focus on skills assessment in isolation from other factors, in both the study and the critique, is too narrow: the data would appear to have more in common with the learning curves of Starkes and others (see 3.1), than with definitive metrics of skill or ability.



(a)

(b)

Figure 2.13: Tissue damage metric as (a) raw score, and (b) log-log plot (Figure (a) from O'Toole *et al* [308], (b) collated from the data in (a))

The apparent improvement in performance over the session seems to have motivated the follow up study by Murray *et al* [291] which examined the learning curve using the BDI simulator (only an abstract summary was published). Five novices completed multiple passes of a virtual needle through a target overlying a 'vessel' in daily sessions of twenty minutes. This was repeated for 13–17 days over a 24 day period. Increased performance on the simulator was observed on a 6 metric scale (comprising: time to complete task, accuracy, peak force applied, tissue damage and angle error) from 25.2± 18.5 (mean ± standard deviation) to 73.4 ±7.1, reaching a plateau between 7 and 11 sessions. It is difficult to comment further since these data do not appear to be comparable with the earlier work and no curves or raw data were published. The subject of learning curves, however, is explored further in Section 3.5.1.

2.4.3.4 *Strain gauge assessment/VR simulator*

Moody *et al* [282] presented results of two sets of construct validity analyses: the first, using strain gauges attached to real instruments, and the second, using the down-loadable VR suturing simulation developed by Jeff Berkley [58] at the Human Interface Technology Laboratory at the University of Washington, see 4.3 below.

- *Strain gauge analysis*

  In the first study, strain gauges were connected to surgical needle-holders and forceps to examine contact forces during the insertion of 'purse string' sutures into a bench model (porcine aorta). Participants in the study comprised 2 senior registrars, 2 junior registrars and 2 nurses (novices). Given the small number of subjects, no statistical analyses were undertaken. Results were, however, compared with subjective metrics proposed by a consultant surgeon (quality and symmetry).

  Several metrics for assessment were proposed: (i) mean stitch completion time; (ii) inter-stitch time; (iii) peak grip force; and (iv), hand coordination (based on the *asymmetric chain-model* theory of Guiard [190], see 3.5.10).

  In general the results were well-ordered although discrimination between groups was not equal: the nurses showed a much longer inter-stitch time, for example, and the senior registrars were distinguished by the use of larger grip forces.

  The analysis of manual coordination did suggest important differences between the groups, with senior registrars demonstrating discrete, regular movements throughout. On the other hand, the data for the nurses showed a profound level of development. Although displayed graphically, no quantification of this data was offered.

- *VR simulator*

  In the second study, needle-holders (still with a strain gauge attached) were attached to a PHANToM haptic device, for use with the demonstration simulator produced by Jeff Berkley. The latter uses a sophisticated finite element model (FEM) to compute forces and deformations, described further in 4.3.4, although only one device is supported.

  This study comprised 20 students (novices) who were required to perform 10 trials of one stitch, each of 4cm length (graphically). The participants were split into 2 groups for which the simulation was run with and without force feedback. The metrics analysed were: (i) stitch completion time; (ii) maximum force applied; (iii) length of suture; and (iv), straightness of suture.

  Comparing the first trial with the last, significant effects were observed for both time and length of suture. The time and straightness metrics indicated that performance was superior under the force-feedback condition. Forces were also applied with more conviction, which was considered more appropriate, given that this factor appeared to distinguish the registrars in the first study.

The application of force as described here may contradict the results of the BDI study (above, 2.4.3.3). The needle-holder used in the strain gauge study, however, appeared to be of a ‘thoracic’ type, in which there is no clamping mechanism. The surgeon, therefore, has to exert a larger grip force to hold the needle securely when suturing. It is not clear if this force is passed to the tissues involved, although it seems likely. If so, this result is at odds with the ‘tissue damage’ metric of [308] which implied that experts were more conservative with their use of force.

Moody *et al* concluded that measurement of forces and the interaction between hands was of primary importance. In particular the authors noted that: ‘although systems with high physical fidelity are desirable, the simulation in the first study… [had] sufficient fidelity for the training objectives related to the task.’

2.4.4 Suturing in non-VR environments

2.4.4.1 *Overview*

Tensioning and tying off sutures forms a significant proportion of any open procedure, and VR researchers are only just beginning to address this issue, eg. [314]. Bann *et al* [48] have employed video technology with motion sensors to analyse suturing and knot-tying on bench models (see below). For suturing, however, it is argued that VR devices allow better assessment of the trainee where line-of-sight may be lost and the relative position of tools to the wound is unclear: in vascular surgery this may easily occur due to complex anatomy, the depth of the wound, use of bypass tubes, patches etc. Nevertheless, a number of important studies have been completed in this area, which are not VR-based, and are described below.

2.4.4.2 *Bench models and ICSAD*

Bann *et al* performed a 2-stage experiment which aimed to determine: (i) whether the relationship between time and number of movements is fixed over a range of tasks; and (ii) whether time and motion analysis using ICSAD (see 2.2.3) can discriminate between basic surgical trainees (BSTs), higher surgical trainees (HSTs) and experts [48]. For the first stage, the relation between time and motion was found to be variable depending on what skill was being undertaken: simple suturing, suturing at depth, or knot tying. For the second stage, the data demonstrate that for most exercises both the time taken and the number of movements required to perform the task can distinguish experienced from non-experienced surgeons to a significant degree.

The effect of 'rehearsal' was pronounced, however, since in five repetitions of the knot-tying trials the BSTs decreased their movements and the time taken by at least 20%. There was little or no effect on the performance of the HSTs, and the data would seem to indicate that HSTs and BSTs were comparable at this stage (significance not given). Although ICSAD appeared to be capable of providing a rating for manual dexterity, the authors acknowledged that these experiments did not provide sufficient grounds for predicting future learning or optimal performance.

In a similar test, using up to eight different stations in a series of short tests (of *c.*15 minutes, where timing is given), Bann *et al* found that *construct validity* held for the most tests between basic and higher surgical trainees, concluding that: 'The methods of objective technical skills assessment of trainees in the UK are applicable to those in Hong Kong'. Failure to find significant differences appeared to be due to ceiling effects, time constraints (of the test) or, possibly, lack of sufficient training [47].

ICSAD has also been used to assess trainees on a 1-day microsurgery course. Grober *et al* [188] found that economy of movement at baseline correlated well with global ratings by blinded, expert microsurgeons. The trainees (90 resident novices, from different backgrounds) showed significant improvement in hand movements and hand-travel distance after training. A test of stereoscopic visual acuity (using a stereo-capable PC), however, did not correlate significantly with global rating scores and did not suggest that measurement of this ability offered potential for predicting future performance (*predictive validity*).

2.4.4.3 *A battery of bench model tests*

Paisley *et al* [310] examined the progress of trainees over a 6 month period of residency. 36 basic surgical trainees (BSTs), 37 medical students (MSs) and 16 general consultant surgeons (CSs) were initially tested on six training devices (including MIST). After the interval, during which no surgical training was given, 26 BSTs and 36 MSs were retested. A synthesis of the results is presented in Table 2.4.

At baseline, MIST demonstrated a weak negative correlation of surgical experience with task time (see 2.3.2.1), but these differences were apparently lost after 6 months. Four of the other tests, however, still showed significant differences at least between the consultant and BST groups — including the laparoscopic box trainer. Experience (both past and recent) may have favoured the consultants in tests of suturing skills (see 2.3.4 and [69]), but it is difficult to explain the contrast between the two laparoscopic tests, especially given that assessment has been championed as the main strength of VR tools [125, 357, 378].

The data in Table 2.4 may nevertheless suggest another interpretation. The retest phase showed more gains on MIST than any other device, for both students and trainees both in terms of both time and efficiency. The authors concluded that this result seemed to imply a strong practice effect — very strong, in fact, as the improvement was retained for 6 months! The consultants were not retested in this phase, so it is difficult to be more certain, but it may be that rapid learning was taking place, possibly assisted by the novelty of the VR display. Perhaps also, if there was slower growth along learning curves in suturing, this would explain why the suturing assignments were more reliable in assessment.

Task	Description	Baseline correlation with		Contrast between groups	Training Improvement
		CSA	experience		
Knot security	3 throws on one-handed knot. 5 trials at surface and 5 at depth. Tested by Tensionometer	–	–	$CS \approx BST$	none found
Placement of sutures (measured deviation)	Needle aimed at 10 targets on material held taut within a frame; wavering of the needle was not allowed	–	–	$CS < BST$ $BST < MS$	BST
Suture of skin laceration	6cm laceration, assessed by time and checklist	–	–	$CS > BST$ (c) $CS < BST$ (t)	none found
Small intestinal anastomosis	end-to-end anastomosis on artificial intestine; assessed by time and checklist	–	✓ (t,weak)	$CS > BST$ (c) $CS < BST$ (t)	BST (t) (no MS control)
Laparoscopic box trainer	Tasks: (i) transfer of objects between graspers and location on a pin; (ii) uncoiling 1m chord at 10cm taped segments	✓(e)	–	$CS \approx BST$ (c) $BST \approx MS$ (c) $CS < BST$ (t) $BST \approx MS$ (t)	BST, MS (t)
MIST-VR	Tasks (3): sequential instrument-to-instrument transfer; and (6), acquire target and apply diathermy	–	✓ (t,weak)	$CS \approx BST \approx MS$	BST, MS (t) BST, MS (eff)

CS=consultant surgeon, BST=basic surgical trainee, MS=medical student(1st year), CSA=consultant surgeon assessment, (t)=time score, (e)=error score, (c)=checklist score, (eff)=efficiency score

Table 2.4: Table of results, synthesised from Paisley *et al* [310]

2.5 Surgical simulation: a preliminary synthesis

This chapter has so far examined the problem of surgical assessment from several different perspectives, using various methods - learning curves, checklists and simulations - with a mixture of results. For annual evaluation of student development, OSATS-style checklists would appear to be the most reliable method. These ratings are relatively coarse-grained, however, and do not suggest ways to improve training, since they are based around students' performance on other devices. For simulations, much of the work has been based around the concept of *construct validity*, to show that these devices are capable of discriminating experts from novices ie. they can measure some difference between levels of acquired skill. Often, however, the novice group appears to improve quickly. Of the (non-VR) Stortz endoscopic trainer, Scott *et al* (see 2.3.3) concluded:

> Laparoscopic skills training is an established part of our residency program. Data now support that the curriculum we use is effective and relevant to clinical practice. Training should commence as early as possible. Thirty to 35 repetitions over a 2-week period is recommended for novices and junior surgery residents to reach an adequate level of performance. . . virtual reality and procedure-specific simulators may further enhance surgical education and will require validation. Additionally, the durability of skills acquired in the skills laboratory is unknown and will need to be further investigated [369].

Chaudhry *et al* have shown that the initial familiarisation curve using MIST requires perhaps 3 or 4 repetitions and that *construct validity* still holds between basic surgical trainees and non-surgical subjects at 10 repetitions [95]. Work by Jon Beard on vascular anastomoses showed that after 50 varicose veins, assessments of trainees showed little further change [Julian Scott MD FRCS, *personal communication*, June 2004]. Although not tested, it seems likely that a similar number of trials on the BDI simulator would have rendered the novice group's performance indistinguishable from that of the surgeons (see Figure 2.13, and the 'Law of Practice', Section 3.5.5). The observed increase in skill makes these devices a poor choice for evaluating surgical expertise since they are essentially *unreliable* until some notional plateau is reached. Even then, if daylight is no longer detectable between novices' and experts' results, then we are forced to conclude that the system is no longer *construct valid.* Section 3.5.1, below, examines the psychomotor and learning psychology literature to gain a more thorough understanding of the issues relating to acquiring skills and plateaux. In general, however, it would appear that simulators would be much better targeted towards training (with assessments) than assessment *per se*.

In [118], Crossan expressed the hope that: ‘Validation of simulators will eventually lead to certification of these devices. The Medical Devices Agency, who ensure medical devices in the UK comply with strict European Union rules has stated that no certification of simulators exists as yet.’ The Medicines and Healthcare products Regulatory Agency, as the Medical Devices Agency has now become, does not list any simulators under its aegis [11]. Whatever the level of debate, therefore, the influence of VR within UK residency programmes remains minimal. To get a more intuitive sense of simulators in everyday usage, Chapter 3 examines the way that new devices are introduced in aviation and military training.

Chapter 3

Training Research

This chapter begins with a review of early work on learning curves in surgery, where, in the absence of simulators and in the interest of patient safety, only a few small studies have been undertaken. Where simulator training has become much more the norm (such as in commercial and military aviation), the issue of evaluating the training is more relevant and amenable. Published guidelines to test simulators are discussed in Sections 3.2–3.4. This material is examined against findings from motor psychology research to aid a clearer understanding of the principles of skill acquisition (3.5). The chapter closes by making some general recommendations for simulator evaluation, which will be used to guide the design process later.

> ‘No excellence in music is to be acquired without constant practice. I have told Miss Bennet several times, that she will never play really well, unless she practises more … If I had ever learnt, I should have been a great proficient’
>
> - Jane Austen, *Pride & Prejudice (c.1813)*

3.1 Clinical training research

3.1.1 Early research in learning curves

Theorists have been attempting to dissect the origin and development of skills ever since the observations of Bryan and Harter in 1897 with regard to telegraphy. Trainee Morse code operators appeared to reach well-defined plateaux in which no improvement was seen for several weeks, after which progress would seemingly begin again [267] (see 3.5.6). The drive to understand and overcome these regions led to two different approaches which can be categorized as either selection or training oriented. The selection group reasoned that if the 'component abilities' of a task could be identified, those candidates with only a low level of 'ability' could be rejected. This view was therefore deterministic. In contrast, the training approach emphasised the need to find better ways to improve performance, although ultimately, a lower starting ability would probably limit the final level of expertise. Later studies, such as the extensive work by Pickleman and Schueneman, failed to correlate dexterity with expertise, although visuo-spatial ability did appear to be important [316].

3.1.2 Microsurgery

The primary problem plaguing the 'component abilities' approach, Starkes commented, was the inability to account for substantial variation in performance [389]. To examine these theories in a more modern context, she chose to collect data from a dental surgeon who undertook a 5-day training course in microsurgery (the surgeon had no previous experience in this field). Figure 3.1 shows the results of this experiment. There is a marked improvement in speed over the course of the week despite progressing onto more difficult media (surgical glove, rat artery, rat vein); it should be noted, however, that the subject was instructed to perform as slowly as needed to complete the task.

The figure shows a steady increase in consistency, with patency (full healing) being achieved on the last day. A retention test was also undertaken 5 days after the last day: this time, the trainee performed 100% of the required sutures with functional patency. The observed time per stitch was also relatively invariant, but was still significantly slower (by a factor of five) than the recorded completion rate for a surgeon of many years' experience. The figure shows clear adjustments from day to day where new ideas and materials were introduced.

To obtain sufficient data for analysis, Starkes repeated the format of this study in

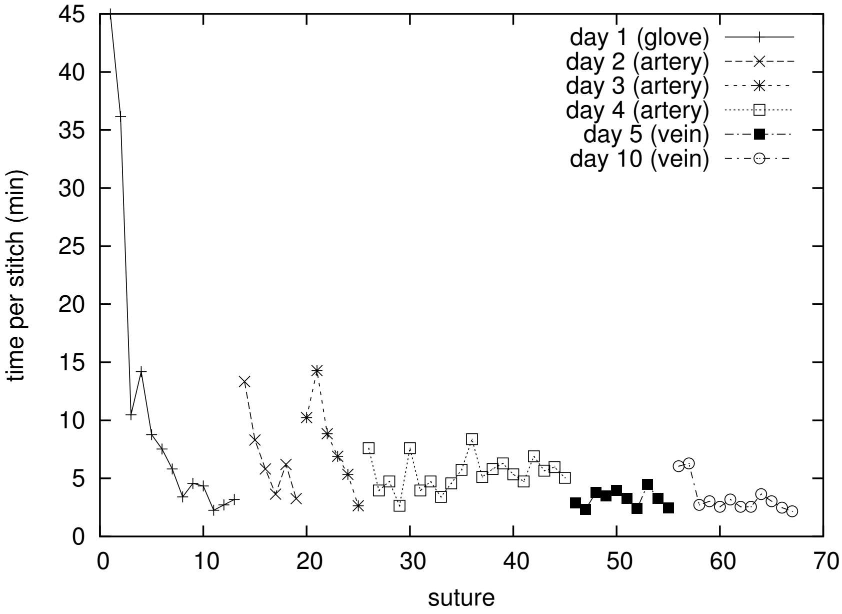


Figure 3.1: Learning curve in microsurgery

(Data from Fig. 12-2, [389])

1998, tracking 13 trainees through a similar 5-day course [390]. By standardising the test on surgical glove material, a very smooth learning curve was obtained and mixed analysis of variance revealed significant main effects for both day and time of day. The author commented, however, that one limitation of this research was that it only addressed the learning and efficiency of suturing movements. Whilst the complexity of cognitive skills and decision making was deliberately kept to a minimum, subjects still had to make decisions about placement of the suture, atraumatic handling of materials, and optimal magnification level to handle the task efficiently. The decrease in time to complete a suture might, therefore, have been as a result of efficiencies in any (or all) of these tasks.

In a later study, Hui *et al* [217] compared the patency rates achieved by two trainees and two experts. The trainees, who had just completed a standard training course in microsurgery, performed 210 consecutive rat femoral vein anastomoses with patency being examined at various intervals up to 14 days after each procedure. These results were compared against those of experienced microsurgeons who performed a total of 64 consecutive anastomoses. The choice of protocol was based on: (a) ease and cost; (b) wide academic acceptance; and (c), the opinion that the thin wall and slow blood flow of venous anastomosis was technically more challenging than arterial anastomosis.

For the trainees, the average patency in their first 25 anastomoses was only 48%, apparently reflecting a steep learning curve. Thereafter, a plateau was reached and although an underlying trend of improving patency could still be seen, 100% patency was not achieved, see Figure 3.2. The difference in the patency rate achieved by the novices before and after their first 25 anastomoses was statistically significant. After this period, the performance of the two groups (experts and novices) was not statistically different. In addition, the time required to perform a single anastomosis, from applying the double microvascular clamp to its removal, was reduced from an average of 45 to 20 minutes. No learning curve was found among the experts, although consistent 100% patency was not achieved for this group either.

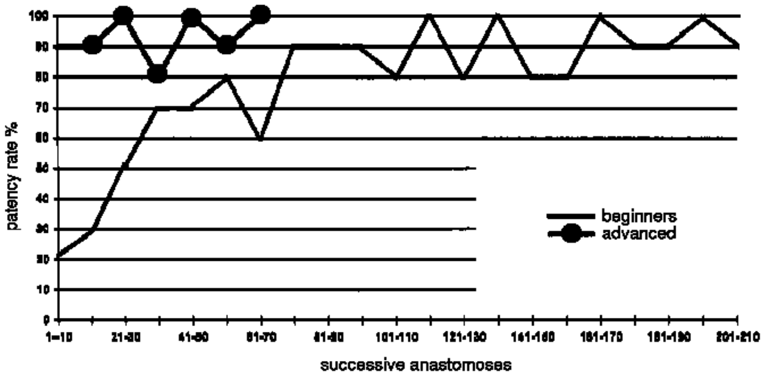


Figure 3.2: Learning curve in microvascular patency

(from Hui *et al* [217])

This form of this learning curve, with its steep initial ascent and gradual levelling off, has been characterised by motor psychologists as 'negatively accelerating' [267, p. 197] (ie. following its mathematical description). This curve represents a power function of skill learning which appears to be described by the classic 'power law' (Section 3.5.5.3).

3.1.3 Laparoscopic hernia repair

Bencini obtained indirect information for laparoscopic hernia repair by the outcomes on patients undergoing laparoscopic hernia repair over a 3 year period at the Florence Main Academic and Teaching Hospital in Italy [54]. For analysis, the 64 patients that were treated consecutively during this period were retrospectively divided into two groups: group 1 included the first 32 patients, and group 2 included the second 32 patients. The results showed that operative times and complication rates were similar, but that bowel injuries were significantly more common in group 1, including patients who were converted to treatment by open surgery. It was concluded that a learning curve was manifested in the decrease of conversions and bowel injuries. Also, it was thought that with improved skills and experience, patients with larger defects probably become candidates for laparoscopic repair.

3.1.4 Biopsy

The initial learning curve for performing biopsy appears to follow a similar ('negatively accelerated') trend. In the review of sentinel node biopsies by Tafra [413], only two of the four multicentre trials examined provided reliable learning curves but these showed a decrease in the false negative rate to 5% after 20 to 30 procedures are performed. Despite several possible confounding factors, the author concluded that the evidence was compelling that surgeons should obtain a minimum experience of 20 cases.

Researchers at the H. Lee Moffitt Cancer Center have adopted a more radical solution to the problem of assessing outcomes whilst protecting patients from unnecessary risk and surgeons from potential legal consequences. Participating surgeons are requested to send their outcomes data of sentinel lymph node (SLN) mapping and biopsy to a secure database via the web [1]. The information is reviewed and analyzed to provide the surgeon with the results of the learning process, but the results are not open to outside scrutiny. Cox *et al* [116] have shown that out of 1,880 cases performed by six surgeons at the Moffitt Cancer Center, an average of 22 cases was needed to achieve a 90% success rate of finding an axillary SLN, and 63 cases were needed for a 95% success rate (a result which echoes the findings of [115]).

Erratic learning curves from many of the outside surgeons led to examination of surgical volume as a potential factor affecting failure rate. The Surgical Volume Index (SVI) was defined as the average number of cases performed in a 30-day period and was calculated for the entire group of 16 surgeons. It was observed that surgeons with SVI<3 had an average success rate of 86.23% which rose to an average of 97.81% for those surgeons with SVI>6. Cox *et al* report that one surgeon whose error rate did not improve as expected, sought reattendance of the lymphatic mapping course, after which there was substantial improvement. The authors intend that the tracking of errors in this format should allow individual surgeons to engage themselves in a continuous quality improvement process [116].

3.2 Military training research

3.2.1 The US Army Research Institute (ARI)

The ARI has tested numerous devices over the past decade. These trials are often at the level of field units (platoons, brigades etc.) in which the old form of training — possibly another simulation — is compared to the new. Examples of research include evaluation of situational awareness [270], new equipment (eg. night vision goggles [319]) and collaborative working on SIMNET and other systems [397]. A few studies aimed at rotary-wing flight simulation are reported below. The scale and frequency of these studies has also prompted the issue of various guidelines, which are discussed in Section 3.3.1.

3.2.2 Transfer of training research

In 2002, Stewart *et al* [396] published the results of a number of trials to develop rotary-winged aircraft simulators undertaken at the ARI throughout the 1990s. The authors observed that the situation still persisted from the 1970s that more attention was often paid to the development of simulators than to supporting training programmes. Simulator developers, perhaps best described as ‘artisans’, had shown considerable skill in getting devices to perform realistically, but had not contributed to the knowledge base for the functional requirements of effective simulation. In short, more research into training effectiveness was needed.

In the sequence of transfer of training (TOT) studies undertaken by the group, the authors sought to establish transfer effectiveness ratios (TERs, see 3.4) for a hydraulically-driven simulator based upon the UH-1 helicopter. Positive TERs were reported for most (but not all) flight manoeuvres pre-trained in the simulator and students in the simulator group required fewer iterations than control participants to reach proficiency. As the visual display and flight modelling systems were upgraded, greater TERs were observed, and the differences among groups tended to become more significant, particularly for less experienced trainees. The authors concluded that a combination of synthetic flight simulation and criterion-based training during the primary phase of rotary wing training had the potential for considerable savings in training time and costs.

3.2.3 PC-based simulators

Increases in computing power and the falling cost of hardware have driven a recent trend to adopt lower cost PC-based systems. As with the earliest fixed-wing simulators, one area where this approach is likely to help is with flight instrument training. Research has shown that the PC-based Aviation Training Device (PCATD) is as effective as procedural instruction for fixed-wing aircraft instruction (at a fraction of the cost) with TERs of 0.16–0.39 (see Equation 3.10, below) being reported. A further study found that just one hours' training allowed an experimental group to perform significantly better in level flight and turning manoeuvres than an untrained control group.

To get FAA approval, however, the physical controls of the simulator need to be able to mimic many flight characteristics. Johnson and Stewart [223] also wanted to test whether similar performance benefits might be obtained for rotary-winged simulations. The authors undertook two phases of 'utility testing', the first with experienced flying instructors; and the second, with students. A total of 16 participants were included which was thought to be optimal to detect most usability problems. Testing was performed by extensive questionnaire. The authors reported good agreement between the groups, with general approval for instrument training, and several criticisms for lack of flying control, especially in hovering.

In a further study, Stewart *et al* [395] wished to compare training using the older Synthetic Flight Training System (SFTS) against a newer PC-based Primary Skills Trainer (PST). In contrast to the PST, the older system (developed in the 1960s) provided a hydraulic platform (requiring expensive maintenance), but no visual feedback. A total of 38 flying students were allocated to a total of 30 hours simulator training in either the SFTS or the PST and then tested after 20 hours instruction in the TH67 Helicopter. Although no difference was found between the groups, the authors concluded that students appeared to the find the older system more difficult to handle and that the PC-based system was clearly superior economically.

3.3 Validity and Reliability

3.3.1 ARI simulator research guidelines

The frequency of non-significant and spurious results has prompted the ARI to publish guidelines for testing new simulator devices. Boldovici *et al* [65] pointed out that where conventional training methods were being compared to new methods (often under different conditions), the meaning and power of these tests was doubtful and, moreover, acceptance of the null hypotheses should not necessarily follow. The authors advised that:

- Testing the hypothesis that one kind of training is superior to another by a stated amount, rather than testing the null hypothesis of equality reduces the chance of making a Type II error, that is, of erroneously concluding the compared kinds of training are equally effective. Using confidence intervals also improves the interpretation of a null hypothesis result.

- Increasing the statistical power of a test does not necessarily require increasing the sample size. Decreasing the variance of scores within compared groups and randomizing variables that we cannot measure or control also results in increased power.

- The results of tests given before the training in an evaluation begins (pretests) help establish whether the compared groups differed in proficiency or in other ways that might confound evaluation.

- Amounts of training exert strong effects — training evaluations that do not equalize or systematically vary amounts of training leave open to question whether the observed effects were due to the compared kinds of training or to differences between their amounts.

- Scores from tests given immediately after training are not reliable predictors of future performance, and tests given at various intervals after training will yield various results. The reliability and validity of scores will increase with the use of multiple post-tests, as will the validity of inferences we make from the scores.

Above all, the authors were concerned that the reliability of any given test should be established, so that valid statistical inferences could be drawn. In particular, they emphasised that reliability gives an upper bound on transfer to the target environment. Following the methodology of Ghiselli, published in 1964, if reliability is expressed as a coefficient between zero (unreliable) and one (reliable), then:

$$predictive\,validity \leq \sqrt{reliability} \tag{3.1}$$

The appearance of Equation 3.1 seems surprising at first sight and references in the simulation literature are scarce. To understand the connection between reliability and the various forms of validity, therefore, it is necessary to give some of the background theory developed in social psychology over the past few decades. This work is introduced below.

3.3.2 Validity and reliability

3.3.2.1 *Measurement*

To understand relation 3.1, a good starting point is the observation by Carmines and Zeller [88] that the process of measuring a given variable is far from simple. In particular, measurement is not just associated with grading objects or events, but must be 'viewed as the process of linking abstract concepts to empirical indicants.' In other words, issues of validity and reliability are uniquely tied to the theoretical considerations which led to the empirical observations in the first place. It will be seen that reliability and validity are in fact tied to the nature of random and non-random errors which are inevitably introduced into most analyses.

3.3.2.2 *Types of error*

Reliability concerns the extent to which an experiment, test or other measuring procedure yields the same result on repeated trials. A given result *always* contains a certain amount of random error and, for this reason, reliability may be defined as inversely proportional to the amount of random error. Validity, on the other hand, is related to the amount of non-random or systematic error which is introduced, usually due to some theoretical issue since the question must often be asked: 'valid for what purpose?' A simple example may help here. Suppose a yardstick[1] were used to measure someone's height in metres. The result may be reliable, since re-measurement always yields (nearly) the same result, but it is quite invalid, since the aim was to measure height in metres.

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[1] $1\,yard \approx 0.9144\,m$

3.3.2.3 *Assessing reliability*

To understand the assessment of reliability, it is useful give a brief derivation of Equation 3.1. Using classical test theory [88, 304], we can write:

$$X = t + e \tag{3.2}$$

where X is the observed score, t is the true score and e is due to random error. If e is truly random, we can predict (over an infinite series of observations) that the expected error, ie. the mean error, will be zero and that we should therefore obtain the true value. Also, we expect the following *correlation* coefficients (ρ) to be zero:

$$\rho\left(e_i, t_j\right) = \rho\left(e_i, e_{j \neq i}\right) = 0 \tag{3.3}$$

that is, no correlation should exist between a given error and true score term, or between two error terms. Extending this to a given population, we have:

$$Var(X) = \sigma_X^2 = Var(t + e) = Var(t) + Var(e) \tag{3.4}$$

since, given our assumptions, covariance terms disappear.

Rearranging, we can define the reliability of X as ρ_X where:

$$\rho_X = \frac{Var(t)}{Var(X)} = 1 - \frac{Var(e)}{Var(X)} \tag{3.5}$$

Hence if all the observed variance is contaminated with random error, then $\rho_X = 1 - (1/1) = 0$ else if there is no random error, $\rho_X = 1$ ie. $0 \leq \rho_X \leq 1$.

To assess reliability, it is supposed that ‘parallel measures’ of the same true score can be obtained. That is, we assume we can get repeat observations X_i of the true score t, which vary by a random error e_i and where the error is normally distributed with a mean of zero and variance $Var(e_i)$. In the simplest case, we can write

$$X = t + e,\, X' = t + e',\, where\, \sigma_e^2 = \sigma_{e'}^2 \tag{3.6}$$

The correlation between parallel measures ($\rho_{XX'}$) can then be expressed in terms of the variances, as:

$$\rho_{XX'} = \frac{\sigma_{XX'}}{\sigma_X \sigma_{X'}} = \frac{\sigma_t^2}{\sigma_X^2} = \frac{Var(t)}{Var(X)} \tag{3.7}$$

(again, given our assumptions in Equation 3.3).

Equation 3.7 is important since it allows an estimate of the variance of the true score and also shows that the correlation between parallel measures is simply the reliability of X, ie. $\rho_X = \rho_{XX'}$. Although only two observations are needed, the more separate measurements are taken, the higher the accuracy of our estimate and, therefore, the greater the reliability. If an infinite number were available, and a correlation matrix constructed, it is possible to show that [304, p.220]:

$$\rho_{tX} = \sqrt{\rho_X} = \sqrt{\rho_{XX'}} \tag{3.8}$$

where ρ_{tX} is the correlation between the true and observed scores and $\rho_{XX'}$ is the reliability of parallel measures. But since ρ_{XY}, the correlation between observations with our current scale (ie. X) and an unspecified second measuring instrument, Y, can never be more reliable than ρ_{tX}, we have (using Equation 3.8):

$$\rho_{XY} \leq \sqrt{\rho_{XX'}} \tag{3.9}$$

and hence the predictive validity (if Y is the criterion measure; see 3.3.2.4 below) is bounded by square root of the reliability of parallel measures (Equation 3.1).

It is useful at this point to describe some of the ways that reliability may be assessed, and the relative strengths and weaknesses of these methods [88]:

1. *Retest method:* One of the easiest ways to estimate reliability is to retest the same people after a period of time. An interval of two weeks may be optimal, though this is not without contention. Too short a period will risk inflation of the reliability estimate due to memory effects, whilst longer periods will introduce greater risk of outside influences, changes in attitudes etc., although this would seem to be more easy to control in tests of skill. A more serious drawback is that researchers are only able to obtain measures at one point in time, since multiple retests are expensive to obtain and often impractical.

2. *Alternate Form method:* As above, the same participants are retested, but an alternate form of the test is used. The main benefit is that memory effects are reduced. But besides the difficulty of devising the new test, a significant problem is that two testing administrations do not allow an estimate of true change given the presence of unreliability in the measure.

3. *Split-halves method:* Instead of repeating the test, the test items are randomly divided and administered to two separate groups. The results of the two groups can then be correlated eg. using the Spearman-Brown prophecy formula. The

main difficulty is then the division of test items, which will tend to influence the correlations generated.

4. *Internal consistency method:* This method avoids splitting or repetition of tests by using measures of internal consistency, eg. Cronbach's alpha, between test items. It has been shown that alpha is a lower bound to the reliability of an unweighted scale of N items, that is $\rho_X \geq \alpha$. Thus, in many situations, alpha provides a conservative estimate of reliability. This is not true, however, if there are systematic differences (eg. learning effects) between parallel measurements [88, p.47][304, p.244]. It might be anticipated, therefore, that in surgical simulations, this method would be valuable for assessing inter-rater reliability (see 2.3.4.3), but would be more of doubtful use for assessing inter-trial reliability (cf. McCluskey *et al*, 2.3.2.4).

3.3.2.4 *Criterion validity*

If the reliability is known, Equation 3.1 gives an upper bound for validity, but establishing (a non-zero) validity is much less straightforward. Carmines and Zeller refer to the principal form of validity as *criterion* validity, which encompasses both predictive and concurrent validity (as defined in Appendix A.1). In both cases an intuitive and obvious external criterion exists either at the present time (hence *concurrent*) or can be tested in the future (hence *predictive*). A written driving test is validated, for example, if it predicts correctly how well people can drive a given type of vehicle. An important feature of this kind of test is that there is a strong degree of correspondence such that correlation coefficients should be significant. Indeed, a good correlation is the only requirement for this type of validity and it should be noted that there may be many equally valid criteria for assessment. One problem, however, is that the validity and reliability of both the test and the criterion assessment need to be verified. Another, at least in the social sciences, is that the opportunity to use such tests is rare.

3.3.2.5 *Content and construct validity*

An alternative is to examine *content* validity of an experiment, in which some attempt is made to specify the range of a particular test domain ie. a 'universe of content' needs to be agreed upon. This too presents considerable difficulties. As an example in social psychology, Carmines and Zeller suggest the problem of measuring an abstract concept such as *self-esteem*. There are certainly no obvious external criteria and it would seem to be impossible to describe the universe of experience. If it is proposed, however, that some novel scale of *self-esteem* may be related to the number of activities (clubs, societies) that someone takes part in, we may then form the *construct* that this new measure is related to 'number of activities'. To give a more formal definition:-

> Construct validity *'is concerned with the extent to which a particular measure relates to other measures consistent with theoretically derived hypotheses concerning the concepts that are being measured'* [88, p.23]

In this case, however, the occurrence of a strong correlation in one test is not sufficient to validate the construct. Instead, the process of construct validation should involve a series of distinct steps, which allows a period of deliberate reflection. Carmines and Zeller suggest the following ideal path: first, that the theoretical relationship must be specified; second, that the empirical relationship between the measures and concepts must be examined; and finally, that the empirical evidence must be interpreted in terms of how it clarifies the initial construct. In effect, a framework of theory and hypotheses must be built around the construct which is only considered valid if a pattern of consistent findings emerges. Indeed, a separate construct is also usually needed — and embedded within the framework of theory — to satisfy researchers that the content of the test is sufficiently wide [304, p.310]. By necessity, this will require endorsement from different researchers after completing a number of different studies.

3.3.2.6 *If the construct is not valid*

If inconsistencies arise, the researcher typically concludes that the construct associated with the main concept is not valid ie. the measure is not appropriate for its intended purpose. The construct may be reformulated (in which case, the process of validation must begin again) but, crucially, previous research employing that measure of the concept must be called into question. Unfortunately, several other avenues of interpretation exist:-

- Perhaps the new construct is reasonable, but it is not positively correlated with the measured variable. In the 'self-esteem' example, it may be concluded that the number of activities is not correlated (though something else may be).
- That the test was not conducted properly or that statistical inferences used were inappropriate.

- Perhaps the test lacks construct validity due to the confounding effects or unreliability of other variables in the analysis.

3.3.3 Validity and reliability in simulation

This section has described at least two important relationships, which may be summarised as:-

1. Equation 3.1, which asserts that predictive validity is bounded by the reliability of measurement. Where doubts about the reliability of a test exist, the validity is effectively zero.
2. An implied hierarchy of validities: predictive and concurrent validity are the most powerful forms, but are usually difficult to assess (and likewise, content validity). Construct validity is often the best alternative, but, in turn, requires careful validation through extensive research.

In Chapter 2, numerous systems were reviewed in which construct validity tests of surgical simulator systems were reviewed. In general, there was good agreement that the performance of novices could be distinguished from that of experts and we might therefore suppose that the *construct* of simulator performance as a measure of surgical skill is valid. Where tested, however, the performance of intermediate level groups was not nearly so clear: see ADEPT (2.2.2), ICSAD (2.2.3), MIST (2.3.2.2), LapSim (2.3.2.3), ProMIS (2.3.2.4), Blue Dragon (2.3.4.2), GI Mentor (2.3.4.3); and was sometimes markedly worse than expected eg. CathSim (2.3.5.2) or even entirely inverted eg. Figert *et al* [157] (2.3.3). It is argued that these anomalies give significant cause for concern with respect to the construct validity approach. At the very least, some level of reflection (consistent with recommendations in 3.3.2.5) is needed. Before returning to this subject in Section 3.6, however, it is necessary to bring in further background material from other psychological perspectives. Section 3.4 discusses attempts to use deliberate training methodologies in simulator evaluation and Section 3.5 gives an introduction to issues motor learning psychology generally.

3.4 Models of transfer

3.4.1 Transfer effectiveness

Bradshaw *et al* have observed that the theory of 'identical elements' remains nearly as pervasive now as when originally advanced by Thorndike in 1906. The main tenet of his theory was that learning was not general — transfer could only occur where identifiably similar elements of the task occurred. In modern testing, however, the issue of which elements to vary in psychological research remains unsolved. A common approach in aviation is to use *subjective estimates of transfer*, in which experts are asked to complete detailed questionnaires on given simulators. Although, good agreement can sometimes be found, the results are usually less than perfect [67].

To avoid such subjective measures, hundreds of transfer models (eg. Equation 2.1), have been proposed since the earliest LINK trainers of the 1940s [195]. One which is still commonly used is the Transfer Effectiveness Ratio (TER), which may be given as:

$$TER = \frac{Task_c - Task_s}{T_{sim}} \tag{3.10}$$

where $Task_c$ and $Task_s$ are respectively the mean time (or number of trials) required for the conventionally- and simulator- trained groups to reach some criterion level on the target task, and T_{sim} is the mean time (or number of trials) that the simulator group spent in the simulator.

A common problem with these models is that evidence to support particular transfer functions has proved to be fragmentary, although Roscoe and Williges [343] argued that the shape of these functions seems to be supported even if the specific values are not, see Figure 3.3. Using an 'incremental' variant of TER (ie. ITER in the figure), for example, this figure purports to show that training effectiveness diminishes after around 5 hours' practice in the GAT aviation trainer.

In the ARI guideline document [65], Boldovici *et al* demur from presenting such figures for several reasons. Firstly, since the reliability of the terms in the numerator is often not sufficiently well established (or published), the numerator may effectively be taken to be zero. Secondly, since the TER does not stem from a controlled study design, the results may be masked by practice or unrelated effects. The authors' conclusion was frank:

> Our advice is to avoid using transfer formulas and transfer-efficiency

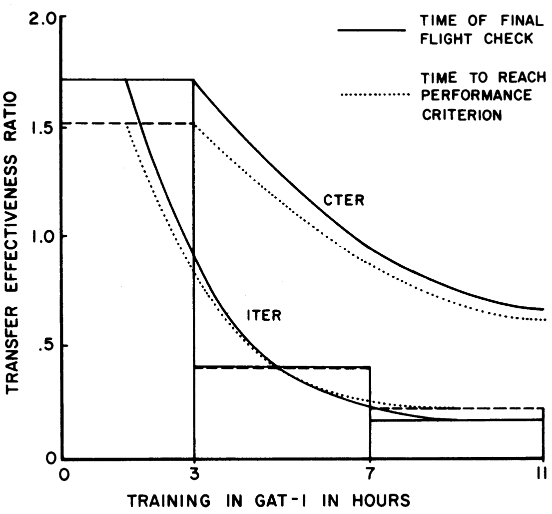

Figure 3.3: Transfer effectiveness for the LINK Gat-1 trainer

(from [343])

> formulas such as the TER. Use conventional analyses of raw scores instead. . . when evaluators do not report conventional analyses of raw scores, we wonder, and hope you will too, whether the evaluators don't know any better. . . the light shed by their work on transfer is not worth the candle.

The justification for seeking expressions such as TER is that they seem to offer a very straightforward method of calculating potential cost benefits. To obtain a reliable estimate of TER, however, identical groups each ideally of 30 or more students must be trained over a period of months to a high degree of proficiency. In other words, a paradox arises that accurately assessing the TER becomes a very expensive proposition [67].

3.4.2 'Above Real-Time Training'

Whatever the doubts about particular models of transfer (see 3.4), studies have consistently shown that simulator training has led to improved performance for aviators, especially in fixed-wing aircraft. Simulators have also, in general, been more effective for practising parts of the task, particularly take-off and landing, rather than the whole experience. Gains on transfer testing, however, have usually been shown to level off after about 25 missions [89].

An intriguing extension of research into transfer is the development of 'Above Real-Time Training' (ARTT). During the late 1960s and early 1970s, test pilots complained that real life events seemed to occur at a quicker pace than in the simulator, even though the simulator events were running at the same speed as real life events. In response, researchers accelerated the simulations and pilots soon endorsed the change, claiming it more closely approximated real life conditions. Transfer studies in gunnery simulation, air traffic control and aviation tactics have subsequently endorsed that ARTT-trained personnel are better able to cope with emergency actions when tested in virtual or real world situations running in the normal time frame [276].

3.4.3 Quasi-transfer

3.4.3.1 *Early research*

Some of the earliest work in quasi-transfer (QT) was undertaken by Lintern *et al* during the 1980s [414]. In principle, the idea is very simple: if a particular feature of a simulator is to be assessed, two groups are trained, one with and one without the feature. In normal transfer experiments, both groups would then be tested to some criterion level of performance in the real task, aeroplane etc. In QT experiments, however, the groups are tested in a simulator, which may be the same as used for training or re-configured to have the feature of interest activated or deactivated, according to the aims of the evaluators.

For many years, flight training research proceeded under the implicit assumption of correspondence between transfer and QT. Using landing as the criterion task, Taylor *et al* [414], found that results in testing this assumption were mixed. Low levels of scene detail (very basic, given the graphics capabilities of the time) were found to show some degree of correspondence in student landings of real aircraft, although this factor was not significant in the QT results. By contrast, augmented displays, in which some groups were aided by 'F-shaped' poles to either side of the virtual landing strip did not seem to aid transfer but showed significant effects in some of the measured parameters of the QT tests. These results were by no means convincing. Given the limitations of simulator fidelity at the time and the difficulty of assessing the same characteristics in genuine aircraft (students were rated by their instructors), the results did give some encouragement.

3.4.3.2 *Recent QT designs*

Using more capable tracking methods, such as the Global Positioning System, and more faithful simulations, some of these issues have been overcome. Recent concerns in the literature have focused on motion cueing, which remains limited compared to the aircraft-motion in real space. Moreover, due to the digital simulation process in the host computer, the simulated aircraft output (the visual displays, the instruments, and the motion system) was found to be disturbed by different time delays, with consequent negative training results [213].

Concerns by the FAA over the effects of these disturbances has led to the funding of a very large project at the American Institute of Aeronautics and Astronautics (AIAA) [84, 85]. Using a QT design, 'motion' and 'no-motion' trained groups were found to have similar results in testing, and later enhancements appeared to cause the 'motion' group to overreact. Only in reaction to certain adverse conditions, did motion cueing appear to help. Elsewhere, the technology was not thought to have provided sufficient motion to be effective. The authors also acknowledged that although the QT design still needs to be thoroughly validated, empirical support has been found by many years' usage as a stand-in for the aircraft in total flight training.

An interesting variation, known as *backwards quasi-transfer*, was demonstrated to be effective by Goettl [179]. In this study, three training groups were given simulator-based flight instruction. The first group received whole-task training, the second group received part-task training concentrating on the critical components of the task and the third group undertook part-task training on non-critical elements of the task. The groups were then tested on a series of VR 'slalom' courses. The first two groups performed equally well, and both were significantly better than the third group. Goettl and Shute [180] argued that assessment of backward transfer is crucial for identifying the relevant and irrelevant component tasks: elimination of component tasks irrelevant to the criterion task should render the part-task training regime more efficient.

In some circumstances, especially wherever hazards in field testing might arise — such as in simulating live fire — QT exercises may be the only choice for estimating transfer. Boldovici *et al* pointed out that as the fidelity of simulators has improved, the QT protocol has developed three important strands: firstly, for estimating how training and testing conditions affect retention and transfer; secondly, to permit the collection of repeated measures by repetitions of individuals' or units' performance, so that test reliability (and hence statistical power) can be increased; and finally, to help refine future experimental designs [65].

3.4.3.3 *QT in surgical simulation*

To the author's knowledge, only one QT experiment has been attempted within the field of surgical simulation. In previous work, Ström *et al* [400] verified that the Procedicus Key Surgical Activities (KSA) simulator produced performance gains (in terms of time and efficiency of movement) after one hours' practice on both the KSA and MIST devices; the KSA simulator provides similar targeting exercises to MIST, but also provides haptic feedback and realistic anatomical graphics. More recently, however, Ström *et al* [401] used a QT design to assess training with the Procedicus MIST, KSA and Virtual Arthroscopy (VA) Shoulder devices against performance on another simulator, the VA Knee device. A post-test only design was used, in which the order of training/testing is given in Table 3.1.

Experimental group	Control group
1 hours' training on Procedicus MIST, KSA and VA Shoulder devices	no training
post-test, VA Knee device	

Table 3.1: Quasi-transfer test by Ström *et al*

The aim of this study was to test the assumption that performance in the Procedicus VA Knee Simulator would not improve after training of novices in other simulators where visuo-spatial components were dissimilar. Arthroscopic surgery was chosen as the test case because it is generally considered a difficult endoscopic procedure, since movements are performed in a very complicated anatomical environment. The comparison of the two groups did not show significant difference between the groups and the failure to find correlation between scores on the various devices appeared to provide support for the authors' claim.

The study appears to violate two basic premises, however. In the first place, a non-significant result does not lend support for any particular hypothesis[2], since the experiment itself may be flawed [65, 250]. In particular, the probability of Type II errors (accepting non-significant results by mistake) does not appear to have been

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[2] To give a common analogy: claiming that a non-significant result is evidence of the null hypothesis, is to equate a 'not guilty' verdict with innocence [297]. In most legal systems, however, only 'guilt' is ever established.

appreciated (see 3.3.1). Secondly, the QT section of the study attempts to compare the 'no training' condition with that of training on the MIST/VA Shoulder/KSA simulators by testing with a different simulator (the VA Knee). A more appropriate QT design, eg. following the work of [414], would have compared training on the VA Knee simulator with training on the other simulators, by post-testing both groups on the VA Knee device.

3.5 A psychological perspective

3.5.1 Ability and skill

Earlier in this document, it was conveniently assumed, following the suggestion by Cuschieri (see 2.2.1 and [356]), that ability was something innate and unchangeable, whilst skill was some property which could be developed. This was a reasonable starting point, but it is now certain that abilities do change (see [423]) and, in the face of this, it is disconcerting that no definition of 'skill' or its acquisition has even been attempted.

The historical review by Adams [31] pointed out that analysts have been struggling with a definition of skill for decades, although that proposed by Pear in 1927 seems to have left its mark in the literature: 'The concept of skill which is proposed is that of integration of well-adjusted performances, rather than a tying together of mere habits. In Man, at least, skill is acquired and fused with natural aptitude.' Pear later adapted his definition to state 'muscular performances ', but psychologists ever since have debated whether 'skill' should include cognitive as well as physical abilities. Adams preferred to leave a more open viewpoint and listed three important properties:

- Skill is a wide behavioural domain, which has included a wide variety of behaviours which are nearly always complex.

- Skill is learned. A useful clarification (especially for simulator research), was offered by Guthrie in 1952: 'skill consists of the ability to bring about some end result with maximum certainty and minimum outlay of energy', but investigators should not be constrained to consider only the highest grades of performance.

- Goal attainment is dependent upon motor behaviour. Any behaviour that is skilled involves combinations of cognitive, perceptual and motor processes, albeit with different weights depending on the task.

A brief survey of the psychology and psychomotor learning literature is given here, firstly, so that the necessary concepts related to performance can be defined and secondly, so that some of the design features of various simulators described in this review can be reappraised.

3.5.2 Knowledge of results (KR) and performance (KP)

Edward Thorndike, one of the fathers of learning psychology, left a legacy which was debated long after his death. His ‘Law of Effect’ supposed that a given subject has many responses available in his or her repertoire, some of which occur in the learning situation. Eventually one of the responses leads to reward and is strengthened, increasing the probability of its occurring and being strengthened again. Learning did not need the intervention of conscious thought processes, but was the automatic strengthening of a habit connection between a stimulus and a response.

In one of his most famous experiments, blind-folded subjects were asked to draw lines of varying lengths. To within a certain tolerance, 13% of the lines drawn were ‘correct’ in a pretest without KR. In the test phase, subjects were informed whether they were right or wrong (ie. given KR) and the percentage correct rose to 54.5% after 4,200 lines had been drawn. With practice repetitions alone, this percentage remained unchanged over the drawing of a further 5,400 lines. Later work supported this result and showed that KR given as a quantitative error produced even faster learning [31].

In this experiment, the feedback was *extrinsic* (given externally by test supervisors), since the participants were blindfolded, but had they been able to teach themselves, feedback could easily have been *intrinsic*. Modern analysts continue to emphasise the role of KR for motor learning (but see 3.5.8), but another valuable technique is to give feedback on limb (hand etc.) movements (known as KP). Research has consistently shown that the provision of error information is more effective for facilitating skill improvement, although there is some debate as to the quantity or quality of information provided. Also, feedback given when not requested, or in too complex format, can depress performance [267, p.275–6].

By its nature, however, kinematic feedback is very difficult for performers to assess themselves and is one reason why coaches and physiotherapists are needed. KP is therefore nearly always *extrinsic*. Another important distinction is that KP is usually independent of the results of the action (KR).

3.5.3 Individual differences

A good deal of the early research in motor psychology was focused upon the problem of assessing 'individual differences' (ie. abilities), to allow prediction of future performance (of pilots, telegraphers etc.). The original contributions by Thorndike (see 3.4 and 3.5.2) were reanalysed by Kincaid in 1925, who decided that no decision could be made about individual differences unless common measures were used (see [31]). The essentials of her findings were that:

- Scores were reliable, ie. scores on adjacent trials were highly correlated
- Correlations between initial and final performance were positive: subjects tended to maintain their relative standing with practice
- Levels of initial performance and gain were negatively correlated: subjects with higher initial performance learned at a slower rate.
- Means, variances and correlations say little about the absolute differences between the scores of each set. Kincaid used the coefficient of variation (standard deviation divided by the mean) to adjust for this. Two-thirds of the studies she reviewed had a smaller coefficient of variation by the end of practice.

A later reanalysis by Reed in 1931 was forced to concur: individual differences tended to converge with practice. Despite a doubling of research efforts during the war, these problems were not overcome and although a handful of motor trials appeared to be valid for selecting pilots, greater weight was always given to printed tests. In the decades following the war, the main contributor to this field was Fleishman, who defined an extensive set of motor ability categories (reaction time, movement time etc.) which are still in widespread use.

Magill [267] (p.224) has observed that researchers attempting the prediction of future performance have taken three main approaches:

- *Prediction from initial scores:* in the classic study by Trussel [424], using 75 sessions to teach juggling, prediction of final performance (over the last four sessions) using data from the first five sessions was little more than the odds of flipping a coin. After 15 sessions, prediction rates improved to about 85%.
- *Intertrial correlations:* using a table format to plot correspondence between trials, it was noted that adjacent trials were much more likely to be highly correlated than trials which are farther from each other. Again, future prediction of performance from early scores was found to be unreliable.

- *Stages of learning:* various researchers have analysed motor learning with respect to Fitts and Posner's model of learning stages (see 3.5.4). In the study by Ackerman [30], the three stages appeared to be related only to skills in which the motor performance aspects of the task are critical for success, and where cognitive requirements do not change in any of the contexts in which the skill may be performed.

Ericsson *et al* regard the search for predictors from the initial assessment of ability as essentially futile: expertise is much more closely related to other factors such as teaching, motivation and, above all, deliberate practice. In their analysis of members of the Berlin Music Academy, they point out that to reach the top of the profession (concert musicians) requires a minimum of 10 years' deliberate practice. Ability and motivation are important, moreover, because they facilitate practice, rather than providing a substitute. Practice must also be highly specific as a similar rule of thumb is described for other skilled performers, such as chess masters. Grandmasters practice and memorise game plans for many years before they can expect to achieve success. As a result they display remarkable skills for recalling the position of chess pieces after examining any board for a few seconds. That is, *unless* the pieces are placed at random, in which case their performance is little better than anyone else [148].

3.5.4 The acquisition of skill

There is is some agreement amongst researchers that the acquisition of skill can be seen as phased process, albeit the phases are not always discrete. Fitts and Posner [159] advocated three phases:

- *Cognitive:* perceptual cues have to be taught or explicitly learned, probably in a simplified version of the task.
- *Associative:* responses that must be learned start to become readily available, old habits are erased and errors are gradually eliminated.
- *Autonomous:* skills become automated, so that they require less cognitive control and are less prone to error.

Rasmussen [328] also described three phases of knowledge states, using a systems theory approach to provide a model of behaviours (see Appendix A.3). Like the Fitts and Posner model, the higher levels demand a greater cognitive load, in which responses are slowed and errors more likely. In the skilled phase, feedback signals relating to the task are received and processed without conscious attention or control. Wentink *et al* [447] have successfully adapted Rasmussen's model to explain some of the complexities and risks associated with laparoscopic surgery.

3.5.5 Laws of practice

3.5.5.1 *Yerkes-Dodson Law*

Psychologists have demonstrated the wide applicability of a number of general rules which have (unfortunately) become known as 'laws', but are chiefly empirical in nature. The Yerkes-Dodson 'law', originally published in 1908, dictates that performance increases with cognitive arousal but only to a certain point: when levels of arousal become too high, performance will decrease . The process is often demonstrated graphically as an inverted U-shaped curve, increasing and then decreasing with higher levels of arousal [102]. Many researchers have corroborated this relationship eg. [203, 329].

3.5.5.2 *Fitts' Law*

A second empirical law was demonstrated by Fitts in 1954. During a simple manual tapping test, where subjects were required to hit targets of different sizes at varying distances as rapidly as possible, Fitts [158] observed the following relationship:

$$movement\,time = a + b\log_2(2D/W) \tag{3.11}$$

- where:

  a and b are constants

  D is the distance moved

  W is the target width or size

This was a demonstration of a speed-accuracy trade-off for two-dimensional movement. In Fitts' terminology the log term was referred to as the 'index of difficulty'. Although motor control researchers have shown that the 'law' may be applied consistently in a wide range of skilled performance situations, including computer interfaces [362, p.163], the cause of the trade-off is not well understood. Most explanations, however, seem to focus on the nature of error control which is applied during performance [267, p.79].

3.5.5.3 *The 'Ubiquitous Law of Practice'*

Observers have shown that extended practice for any particular skill pushes the performance characteristics towards asymptote. Newell and Rosenbloom refer to the 'ubiquitous law of practice': time per unit measured appears to follow a power law, which can be expressed as:

$$T = A + \beta(N + E)^{-\alpha} \tag{3.12}$$

where T is the time per unit (or trial), A is the level of asymptotic performance, N is the number of trials performed and E is 'experience' ie. number of previously completed trials; α and β are positive constants [295]. The authors reanalysed data from many sources including perceptual challenges, simple motor tasks (tracking a cursor, mirror tracing), problem solving (learning card games, decision-making exercises), cigar manufacture and so on. For most results studied, a log-log plot produced a reasonably straight line response, both with the power law and the hyperbolic ($\alpha = 1$) model.

It follows from this rule, that the time and efficiency metrics, which have been used for many simulator studies (see 2.3), are reasonable choices for assessing acquired levels of skill. It would also seem that these factors tend to improve purely through practice ie. without extrinsic feedback on the nature of errors being committed (KR) or particular movement errors (KP). Thus, for training devices where time-related scores are the main features being measured (eg. MIST and ICSAD), improvement may be a by-product of trials undertaken. Caution is also therefore required to ensure that technical aspects of the performance are not marred and that illegal strategies are not permitted (as appeared to occur for the HOPS simulator, see 2.4.2.2).

By contrast, the attempt to evaluate tissue distress in the BDI suturing simulator was more ambitious, since it was aimed directly at assessing technique and providing more appropriate KR (see 2.4.3.3). To demonstrate the 'law' of practice, an example log-log plot is given in Figure 2.13(b) for the 'tissue damage' parameter, and shows a reasonably well correlated fit to a hyperbolic power law function (Pearson r^2=0.872 (experts), 0.803 (novices); $p < 0.005$). The intersection of the fitted straight line responses in this figure would occur at the 53rd trial, suggesting that novices' performance would rival that of the experts after a further 40 trials. Since this point would lie in the region of negative 'tissue damage' (not defined), it is argued that this value forms an upper bound for any possible intersection.

3.5.6 Plateaux

The existence of plateaux in learning curves was first recognised by skills researchers working over a century ago. Training in telegraphy, and in particular, the reception of Morse code transmissions, often appeared to stall with no improvements for many weeks. A possible explanation was that trainees arrived at points of transition where sequences of information were forming letters, then words and finally phrases. These findings are still described in many texts, despite the fact that replications of the original experiments have failed to produce plateaux and that some psychologists have begun to doubt their existence [31]. The phenomenon has been observed in many other experiments, although it remains unclear whether it proceeds from instructional techniques, fatigue or lack of motivation [267, p.204].

3.5.7 Task classification

Several formal systems of task classification have been proposed. Gentile proposed a comprehensive two-dimensional scheme, linking *environmental context* with *inter-trial variability* [173]. The context described several properties:

- in *closed* motor skills, the relevant contexts are stationary, meaning that they do not change position during the performance eg. picking up a cup whilst sitting in a chair. The movement characteristics are invariant and can be initiated at any time.

- in *open* contexts, the environment is moving, so that other people, objects and surfaces must be accounted for eg. returning a ball at at tennis. Successful action requires action at exactly the right moment.

- The forces, masses and other properties of objects that form the environment also dictate the nature of the interaction.

Variability between trials implies that the environment changes between each trial, so that different movements must be continually planned.

In a similar vein, systems theorists proposed that movements could either be *closed-loop* or *open-looped* [31]. In open-loop activities, all the information to carry out the movement must be contained in the initial instructions to the muscle effectors. In closed-loop performance, feedback is compared to some norm to enable an action to be carried out. Central to the closed-loop theory was the explicit rejection of the Thorndikean idea of KR automatically producing learning. Instead, motor learning was seen as a process of acquiring the capability to detect errors intrinsically.

Schema theory was evolved in response to several perceived shortcomings of the closed-loop theory [31, 361, 362]. Central to the idea was that motor functions are provided by a range of different general motor programmes which must be adapted when new circumstances arise. At its core, a motor programme describes a set of rules for relative timing which must be invariant throughout execution of the programme, although the speed of the programme as a whole can be increased or decreased. In the classic experiment by Shapiro [379], walking up to about 6km/h was found to have one set of invariant features, but beyond that, the motion changed to a running action which had separate programme timings. The theory also accommodated *response schema* which allowed feedback to adjust movement if needed.

3.5.8 Training schedules, interference and retention

Perhaps the most important outcome with respect to motor programmes and *schema* theory was the suggestion that the variation of schedules for feedback and training could be productive. Several ground-breaking experiments were to follow. Shea and Morgan [383] tested *contextual interference* effects of training to perform three simple arm movement tasks, say A-C, as quickly as possible under different regimes. Under the blocked regime, participants would perform blocks of task A, then a block of task B and so on. Participants in the random group practiced exactly the same number and type of movements, but in random order. Unsurprisingly the block practice group performed significantly faster during training.

In testing, however, both groups were asked to perform in a blocked and random format on two occasions: 10 minutes and 10 days after the final practice. Whereas the randomly trained group appeared to stay at about the same level as their last performance during tests, the people who had practiced under the blocked regime showed sharply contrasting results. Tested in a blocked order, their results were slightly worse; tested in a random order, their results were very much worse. In fact, asked to recall these movements at random, the performance of the block-trained group was worse than baseline performance prior to training.

Results such as these have generally been attributed to a class of phenomena known as *interference* [332, 457]. One explanation that has been advanced is the ‘forgetting hypothesis’. This supposes that random practice during early rehearsal causes people to generate and reconstruct action plans more effectively later, because they were forced to forget (and recall) the movement more during practice. Another possible explanation is that by varying the conditions of practice, transfer to the target environment is more likely [55]. Other investigators have added to this picture: blocked regimes may be more helpful for younger students or during early training [381, 455]; interference effects would seem to be negligible for some, very simple tasks [274].

The distribution of practice, using the amount of 'rest time' between sessions as a treatment variable, has been shown to be another important variable for retention and transfer. Data shows that massed practice tends to depress performance during training and groups in which the training is distributed would appear to have distinct advantages during retention and transfer tests [384]. However, practicing well beyond the first acceptable plateau region, or *overlearning*, has also been found to increase retention for some tasks which are needed only sporadically. Schendel and Hagman [358] used the example of machine gun disassembly and assembly to show that if the number of trials required to perform the skill correctly *once* is doubled (ie. 100% extra practice), performance is much more likely to be retained [41, 448]. Such performance schedules can, nevertheless, produce negative results: Shea and Kohl [380] showed that in an exercise of pushing a lever with a specified force (175N), a group which practiced using a range of forces was more accurate in retention than an overtrained group who had only ever applied the correct force.

3.5.9 Feedback: scheduling and augmentation

3.5.9.1 ***The functions of extrinsic feedback***

Schmidt and Wrisberg have described four important functions of extrinsic feedback [362, p.283]:

1. *Motivation:* to energise learners into achieving the goals they have set for themselves.
2. *Reinforcement:* to encourage more successful actions and to discourage less rewarding ones.
3. *Information:* to indicate (directly or indirectly) actions for learners to control movements or correct errors.
4. *Dependence:* feedback, of whatever quality, has dependency-inducing qualities, especially if provided too often.

The authors also made an interesting additional distinction between descriptive and prescriptive forms of external feedback, based on the research undertaken by Kernodle and Carlton in 1992 [232]. In this experiment, groups were given feedback on their ability to make an overhand throw with the non-dominant hand, whilst being blinded to the length of the throw by a wall. Groups who only received descriptive feedback (the distance of the throw) were not as successful as those also received cues to more effective throwing motions (advice attempting to 'prescribe' the motion). This suggested that knowledge of results (KR) was not the most effective form of feedback where complex movement activities were required. This result was echoed in a clinical setting by Rogers *et al* [342], who found that training in knot-tying exercises was enhanced when video-tapes of common errors and the correct method of tying were shown first. Groups who saw only one or neither of the video-tapes appeared to be equally disadvantaged.

These findings, and how they relate to training or simulation studies in general, are described below.

3.5.9.2 *Feedback schedules*

The interaction between developing motor programmes and different levels of feedback has proved to be a fruitful area of research in motor psychology. In keeping with the nature of closed-loop and *schema* theory, it seems necessary to allow trainees to develop their own techniques of error detection. For example, providing immediate feedback after each trial (100% KR) has been found to be counterproductive in targeting [36] and tracking tasks [453]. There is also some evidence that trainees may be sensitive to receiving feedback too soon after the end of the exercise, whilst they may be trying to assimilate their next 'action plan'. Various authors have found that, by contrast, many students prefer to select feedback when they themselves feel it to be needed [406]. The survey by Chiviakowsky and Wulf found that most trainees preferred feedback only after a relatively successful trial [96].

It is notable that some simulator systems have drawn complaints from users for providing too much feedback, making the system appear to be overly critical [417]. On the other hand, some researchers have found that more frequent feedback can aid learners in acquiring complex skills, perhaps especially in the earliest phases. Wulf *et al* [458] found that a 100% feedback schedule on a ski-simulator produced more effective performance after 2 days' training (and a retention test on the third day), when compared to groups who only received feedback after 50% of trials. For more experienced subjects, however, such constant feedback affects attentional cues and may reduce performance [53].

More recent research, also using a ski-simulator, but without specific feedback has revealed another interesting trend. Nourrit *et al* [303] found that training sessions over a period of 13 weeks produced profound changes from a highly non-linear damped movement initially to a much more linear function by retention testing at 5 months. During the transition stage, the 2 damping behaviours seemed to be alternately exploited within each trial, indicating that trainees were selecting from a number of possible strategies.

3.5.9.3 *Augmented feedback*

Given this picture, it is easy to see that care should be taken to provide only appropriate feedback. Intrinsic feedback, such as the use of force-feedback, is a common area of difficulty: several studies have shown that where forces were absent (see 2.4.3.4 and 2.3.4) or inappropriate (eg. [85]), performance is detrimentally affected. On the other hand, systems which have attempted to augment the level of extrinsic feedback, such as the real-time 'guide vector' condition on the BDI simulator (see 2.4.3.3), have also had very limited success.

Too much additional feedback can lead to cognitive overload and is often unwarranted. Given in this way, feedback can be demotivating or can lead to the formation of a dependency: performance is raised during practice, but errors are only aggravated if the training aid is removed. Devices for assisting weight-lifters during practice, for example, have been shown to degrade test performance rather than help [422] (and see [267, p.222,290]). Some researchers, however, have found that concurrent visual feedback has been found to be beneficial in older adults (over 60) [454] and in rehabilitation settings [130].

3.5.9.4 *Performance feedback*

Investigations into the requirements for movement feedback (KP) are somewhat rarer, but also seem to show that trainees find this extra information difficult to assimilate, eg. [435]. Focusing directly upon the kinaesthetic properties of limbs has been shown to have a negative effect upon training. In a balancing task on a stabilometer platform, those participants who were asked to focus on their feet performed significantly worse during retention testing than those whose attention was focused upon an external marker [382]. In this test, the concurrent feedback was not withdrawn during testing, but the external focus appeared to help by dissuading participants from taking active control of their movements. It was also noted that those members of external focus groups, after some practice and particularly during the retention test, appeared to move the platform generally more smoothly than the participants in the internal focus group.

3.5.10 Bimanual interaction

The importance of working with both hands has been stressed by a number of authors [45, 160, 206, 225, 336] in both psychological and human-computer interaction domains. Seay *et al* [370] nevertheless found that performance on the *Virtual Workbench* varied using different types of devices but did not significantly improve by allowing the use of both hands.

Direct or symmetric interaction, where both hands are essentially performing the same manoeuvre either together or in cyclic order has been described by Swinnen *et al* [64, 407]. Indirect, asymmetric interaction, however, was not fully appreciated until the work of Guiard [190], which observed that most human actions are in fact bimanual, even if only one hand appears to be playing a role. Writing a letter, for example, involves many movements with the non-dominant hand to position and frame the paper, see Figure 3.4, so that the actual working space of the dominant hand is very small. Moreover, Guiard found that the subordinate hand often plays a leading role, defining a broad 'macro' space within which the dominant hand is able to act much more finely. The asymmetry of left and right-hand movements was observed in a suturing task by Moody *et al* (see 2.4.3.4). This behaviour appears to be natural, since the novices in this study tended towards the leading non-dominant hand action pattern of experts after sufficient practice (although this was not entirely perfected).

There is a further reason to believe that bimanual coordination is relevant here, since several authors have reported that transfer is reinforced between limbs. In the study by Weeks *et al* [445], a simulated prosthetic arm (worn by a fully able limb) was used to examine possible directional effects of transfer by dividing participants (42 able-bodied adults) into three groups: (i) practice with the preferred hand/tested with non-preferred; (ii) practice with the non-preferred hand/tested with preferred; and (iii) a control group (no practice). Although there was no significant bias to transfer direction, transfer was observed in both directions with initiation time (time to begin the task) showing immediate benefits. Interestingly, overall movement time did not show immediate benefits, but did show significant improvements on retention

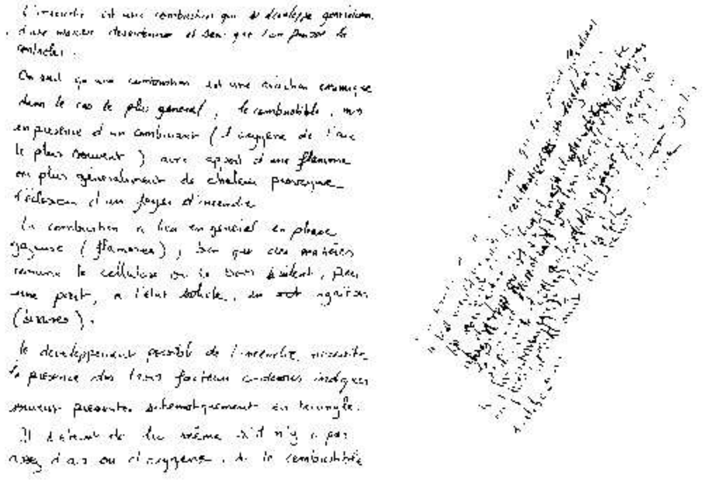

Figure 3.4: Asymmetric division of hand-writing task

(Left: finished letter, right: workspace used as seen from hidden carbon paper. From Guiard [190])

tests 24 hours later.

3.5.11 Part-task/whole-task training

For *complex* tasks (those which contain many component parts) which have little *organisation* (whether the component parts are related), the part-task approach to training provides a reasonable choice for breaking the problem into independent parts ([267, p.238]). Three strategies are commonly employed:

- *fractionization:* the task is practiced on a limb-by-limb basis to target asymmetric activities.
- *segmentation:* the task is broken into successive sub-tasks.
- *simplification:* the difficulty of all or parts of the task are reduced, by reducing the load or speed required.

Simulators are readily adapted to the part-task approach for complex tasks [41, 180], and reductions in complexity of all three types are often needed.

One study which is of further interest in this area lies in the area of Morse code reception (see 3.5.3). Proficiency in this area is still very difficult to achieve and has a high failure rate in terms of trainees. Some researchers have suggested that practising the more difficult components earlier in the schedule has positive benefits [138]. In the study by Clawson *et al* [103], training on the more difficult elements first, however, was not found to be a useful strategy to teach letter discrimination. A further experiment which broke the task into more difficult procedural aspects led to slower performance and more errors in the practice phase, but performance on individual sub-tasks was better retained upon a retention test 14 days later. This group nevertheless found it harder to integrate the component sub-tasks.

3.6 Issues in simulator validation

3.6.1 Training effects and assessment

This chapter has investigated the nature of learning and assessment of skills from several different perspectives. To resolve some of the apparent differences, this section gives a synthesis, which is, in a sense, a continuation of the earlier attempt in Section 2.5. The discussion here focuses upon the BDI suturing simulator described in Section 2.4.3.3, but makes several recommendations which are intended to be more generally applicable. The BDI study initially defined two broad objectives: to assess whether surgical simulators can (a) measure surgical skills, and (b) be used to train surgical skills. Yet, while these aims may seem to be distinct, improvements in adjacent test scores suggest poor reliability (eg. see Figure 2.13(a)) and most skills testing studies have shown similar practice/carry over effects. Another common problem with the *construct validity* approach is that experts and trainees appear to be converging fairly quickly: eg. after approximately 30 trials for the Stortz trainer and perhaps 30–40 trials for the BDI study (see 2.5).

The authors of BDI study concluded that: ‘These data provide evidence that the performance improves (at least transiently) during a single training session’ [308]. The study, however, followed a *block* training format, which has been shown to give good initial results, but very poor retention (see 3.5.8). To determine whether lasting learning has occurred requires a knowledge of learning curves, retention and transfer characteristics which have generally been overlooked in most surgically-based simulations. Indeed, it is instructive to reflect that, although construct validity studies are common in social psychology, this kind of *divergent validity* approach (in which groups are expected to diverge [304, p.93]) has rarely been adopted elsewhere (see [415] and [53] for exceptions) and is unknown, as far as the author is aware, in flight simulator studies. A number of possible explanations may be offered:

1. *Quasi-experimental nature of the test:* in the form of test shown for the BDI simulator in Figure 2.13(a), several variables seem to be being manipulated: (i) firstly, the experience of the participants has determined entry into the novices' or experts' group; and secondly, the 'explanatory' variable (along the baseline of the figure) is "number of trial". Since the experimenter cannot genuinely assign the first variable randomly, this test is therefore of the form of a 'quasi-experiment'. Leik [250] has pointed out that although such tests are often the only practicable way of performing some experiments, and that their *external validity* ('applicability' to the real world) is often very high, circularities in the *internal validity* of these tests are common (see A.1 and [233]). Several such tautologies can be described here. In the first place, an appropriate null hypothesis might be stated as 'there is no difference between the expert and novice groups' — although clearly this premise is false. This suggests that the test is fundamentally *weak*, especially if the participants are very experienced/inexperienced. Also, if the test were a reliable assessment of surgical skill, the number of the trial should not be an issue, and it is unclear why this variable is under test.

2. *Criterion-based assessment is preferred:* in other fields, where strong criteria are available — such as, say, an ideal 4° descent path for flight simulations — it is possible to assess trainees directly according to their performance. Although several research groups have attempted to produce such 'gold standard' criteria for surgical procedures (eg. using daVinci, see 2.3.6, or Markov modelling [344]), the complexity of this problem does not suggest that easy solutions will be forthcoming for surgical applications.

3. *Usability studies:* where experts and trainees have been tested together in relatively short-term evaluational studies, the designers of the test have preferred to obtain questionnaire responses rather than a direct comparison of test scores (see 3.2.3).

4. *Use of time and efficiency metrics:* for most *construct validity* tests, significant differences are only obtained for response variables which are based upon time and efficiency metrics (including the 'tissue-damage' variable of the BDI

study). This suggests that only the proficiency of subjects is being monitored and that the VR system is really only providing (expensive) clocking facilities: training might, therefore, be as successful using less costly synthetic substitutes. One exception to this pattern was the real-time guide vector condition of the BDI study, which despite an interesting effect upon performance, did not produce any lasting benefit. (This finding is in line with other motor psychological research, which suggests that such feedback can produce dependency, see 3.5.9.)

5. *Power of the test:* researchers at the ARI and elsewhere are emphatic that the statistical power of the test should be estimated beforehand and stated. This requires that the reliability of the test should be established, possible confounding variables should be controlled and, ideally, that some specified amount of learning should be intended. Given the extraordinary length and variety of surgical training, however, the power of any particular simulator test would be very difficult to foresee.

3.6.2 Implications for construct validity testing

In Section 3.3.2.5, it was argued that construct validity requires a rigid framework of theory and hypotheses which must be widely tested to be gain acceptance. In general, efficiency and proficiency metrics have been consistently shown to discriminate between experts and novices (with no prior experience). Before a simulator can be used for assessment, therefore, we should expect tests to show significant differences between these groups, at least on these metrics.

The nature of this construct, however, was brought into question for several other reasons:-

1. Section 3.3.3 pointed out that, where tested, intermediate level groups most often did not show the expected level of discrimination and sometimes performed poorly with respect to their less experienced counterparts. This suggests that skill cannot be treated as a simple, smooth progression between novice and expert states.

2. Some authors made incorrect inferences about the failure to show construct validity, eg. Broe *et al* (Section 2.3.2.4). In the first place, non-significant results do not allow inferences to be drawn [250]. But more importantly, it is necessary to understand that construct validity requires a consensus. If

the framework which supports the construct is undermined, it is not possible simply to draw the opposite conclusion (ie. that the simulator is not a good assessment tool). Instead, the construct itself needs to be re-examined [88].

3. Failure to assess reliability: whilst inter-rater reliability may be established using techniques such as Cronbach's alpha (eg. Section 2.3.4.3), such techniques should not be used to assess inter-trial reliability as learning effects will inflate the estimate. Multiple retests and retention tests are much preferred in training-oriented studies elsewhere.

4. The validity of simulators as a test of surgical skill is also undermined if novices can be shown to rival experts after a relatively short training period, since the simulator appears to be unreliable. Although rarely tested, this often appears to be the case.

Given these limitations, the preference for criterion-based assessment in other fields is not surprising. But it is notable that by employing experts, construct validity tests would seem to be attempting to define an appropriate level of 'gold standard' performance against which trainees can be measured (though this step is rarely taken). Several systems have now been developed with the objective of defining gold standards for surgery. Until these are widely accepted, however, this debate will need to be resolved. It is suggested that these issues should trigger a period of reflection about the nature of the current validity construct. At the very least, it would be better if the framework were adapted to allow training-related issues to be supported.

3.6.3 Fidelity

The different rates of learning between expert and trainee groups observed in the BDI study are also of interest, since expert performance should, by definition, be at asymptote (see Figure 2.13(b)). Motor learning psychologists would associate this level of proficiency with the *autonomous* phase of Fitts and Posner's model (see 3.5.4). That learning should still be occurring, therefore, suggests that the novel form of the task/interface is incurring an extra cognitive load, one which must be overcome in addition to learning the task itself by less experienced trainees.

Furthermore, for surgical simulations, the complexity of the task *in toto* indicates that the task should be simplified (segmented etc.), so that it is possible to practice particular sub-tasks in sequence. Sub-tasking is an approach which is recognised as a valid technique, although a major concern is that deliberate practice is also required when the individual wishes to reassemble these sub-tasks into the full procedure ([362, p.218]). Another concern is that the fidelity of the simulator may be compromised by over-simplification. Whilst this may be true for some situations, several authors have warned that fidelity in simulation is a question of taking mitigating action and assessing diminishing returns. Reder and Klatzky [332], for example, pointed out that transfer is better where: (a) training is distributed, (b) the situation does *not* mirror the target task exactly; and (c), variable duration and task parameters are practiced (see also Bortoli *et al* [50]). Indeed, Taylor *et al* [414] observed that there is considerable evidence that faith in high fidelity is misplaced, and that 'planned departures from similarity' can actually enhance transfer.

3.6.4 Recommendations for training

If direct assessments of surgical skill are not yet reliable enough for widespread use, it is argued that surgical simulators should be aimed at fulfilling training requirements including, if possible, the period of the first 20-30 or so procedures when patients are most at risk from surgical error (Section 3.1). An understanding of: (i) the quality and amount of training required; and (ii), the degree of consistency needed in learning curves (both collective and individual), should be the main objectives of research in the near future. Above all, it is hoped that this section has underlined the need for repeated testing over a considerable period (and preferably under a variety of conditions), before a given trainee assessment is declared valid.

Indeed, data from other training studies suggest that a programme of 'overtraining' would be beneficial. We might recommend, say, that twice the number of procedures during the risk period are performed on the simulator. An ARTT form of training might also be adopted in which compressed time, or, perhaps more appropriate for surgery, compressed space scenarios are employed. Relative assessments of improvement would then be available along with transfer and retention information. Requirements for remedial training should also be identified to bridge the gaps between sub-tasks taught on the simulator and the full procedure.

Some doubt was thrown onto the usefulness of simple models of transfer, such as the TER. Instead, several research groups have recommended carefully designed quasi-transfer studies to examine particular aspects of simulator construction eg. hexapod motion of aviation simulators [84, 85]. Evidence for the usefulness of quasi-transfer studies is rather empirical in nature, but substantial nonetheless.

Chapter 4

Modelling Solids and Forces

This chapter reviews the literature for deformable modelling and interaction with ‘soft objects’. It begins with a description of the complexity of the human sense of touch and the requirements to create an adequate level of VR immersion. A brief survey of the available force-feedback hardware is then given. Section 4.2 examines the research into standard tissue responses under *in vitro* and *in vivo* conditions. The challenge of using these constraints to build realistic deformable models in real-time systems is examined in Sections 4.3–4.6.

‘The raising of the capstones of chambered tombs presents few difficulties if it assumed that the mound surrounding the chamber was first built up to the level of the tops of its walls. . . the main necessity would be the very careful strutting of the chamber walls to resist lateral pressure. . . the packing being removed, not perhaps without some trepidation, only after the capstones were all in place.’

- R.J.C. Atkinson, *Neolithic Engineering*, Antiquity Vol.35, 1961

4.1 Haptic interfaces

4.1.1 The human hand

Human skin, Figure 4.1, contains a large array of sensors. Meissner's corpuscles represent about 40% of the hands tactile receptors and lie just below the epidermis. Since they move with the ridges of the skin, these receptors can best detect movement across the skin, giving feedback on velocity. Merkel's disks form about 25% of the receptors and having a disk-like ending can respond to pressure and vibrational information. Pacinian corpuscles are the largest receptors (making up about 13% of receptors) and function as accelerometers. Ruffini corpuscles (about 19% of receptors) can detect pressure, shear forces and thermal changes. Hairy skin has an additional receptor which can also detect movement across the surface [82].

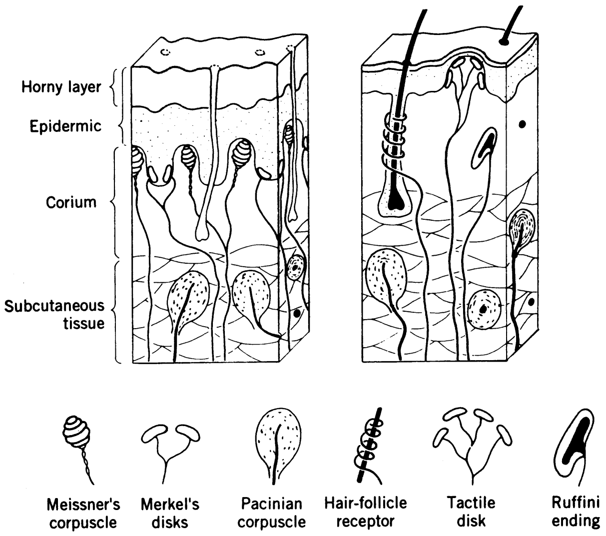

Figure 4.1: Human skin tactile receptors

(From [374])

The electromechanical properties of these sensors varies widely, but allows discrimination between contact points to within a few millimetres and resolution between consecutive force inputs up to frequencies of about 320Hz (pain and tactile receptors act orders of magnitude faster). By the Nyquist criterion, this suggests that haptic devices should aim to generate force samples at twice this limit and most modern devices claim to be able to represent *c.*1000Hz. Early efforts were able to recreate a number of tactile effects (eg. sandpaper [277]) but, unsurprisingly, were generally unstable. A significant challenge was the 'virtual wall' problem — stiff surfaces and sudden impacts were very difficult to reproduce [105]. One compromise which partially solved this problem was the 'god-object' display proposed by Zilles and Salisbury [352, 464], in which objects were allowed to inter-penetrate, generating forces at touching surfaces according to the 'depth' of interaction.

4.1.2 Glove-based devices

Crossan [118] surveyed a range of glove type devices with respect to the exploratory principles of [246] (see 2.4.2.2). Several variations have been developed to target different skin sensations. The Cybertouch glove [25] available from Immersion is one example of a vibrotactile device. Feedback is presented to the user through 6 vibrotactile stimulators; one on each finger and one on the palm.

Kajimoto *et al* [226] have developed an electrotactile mouse. The authors argued that one advantage of the use of electrotactile displays over vibrotactile arrays is that they avoid mechanical difficulties. Confining the sensation to a small, focused area was nevertheless a significant challenge. Some users also felt that the electrical stimulation was invasive. In contrast, the Teletact II device, developed by the Advanced Robotics Research Device Centre, is an example of a device that supplies pneumatic stimuli. Feedback is presented to the user using thirty small air pockets across the palm of the hand [399].

Few devices have attempted to apply force feedback directly to the hand. One exception is the Rutgers Hand Master (I and II) [82, 83], Figure 4.2, which allows 1 degree-of-freedom (dof) forces to be applied to the thumb and three forefingers. Glove-based devices must usually be used in conjunction with other translational devices if haptic objects in 3D space need to be represented. To the author's knowledge, none of these devices has been used in surgical simulation, presumably because positional feedback has been assumed to be of primary importance. It is also likely that there would be significant problems in calibrating glove-devices with positional haptic devices.

4.1.3 Translational devices

The PHANToM from SensAble, see Figure 4.3, was the first type of positional device to be commercially developed following the work of Salisbury *et al* on 'god-objects' [352]. Pen-shaped or gimbal end effectors are allowed at the endpoint of the device

Figure 4.2: Rutgers Hand Master II

(from http://www.caip.rutgers.edu)

Figure 4.3: PHANToM Desktop haptic device

(from [373])

which has 6 dof (translational and rotational) input and 3 dof (or optionally 6 dof) force output. Hollerbach has pointed out that the workspace of these devices is always an important issue [211]. The smaller Desktop PHANToM permits a workspace of 160×120×120 mm, with a continuous maximum force output of 1.75N (maximum exertable 7.9N). The larger PHANToM models permit a workspace of 900×900×300 mm and force output of 3N continuously (or 22 N maximum) which allows calibration with virtual workbench devices [68].

Whilst the PHANToM devices might be thought to relate to activities with the hand and forearm, the HapticMaster developed by FCS Robotics [2, 431] (Figure 4.4) accommodates arm movements within a volume of 360×400×640 mm with a much larger force range, up to a maximum output of 250N (100N continuously) with a resolution of 0.01N. This device can therefore simulate more forceful lifting or pulling activities, perhaps, most obviously, in rehabilitation tasks.

Figure 4.4: FCS Robotics HapticMASTER

(from [2])

Although a pair of PHANToM devices can be used in an adjacent, overlapping workspace (see 2.4.2.3), the SPIDAR haptic device relies upon tensioned cables which control eight fingertip attachment devices and allows close working of both hands, see Figure 4.5. The concept is scalable to almost any workspace and preliminary evaluation of a bimanual task has demonstrated remarkable effectiveness [238, 438]. Rotational input or output with the SPIDAR and HapticMaster de-

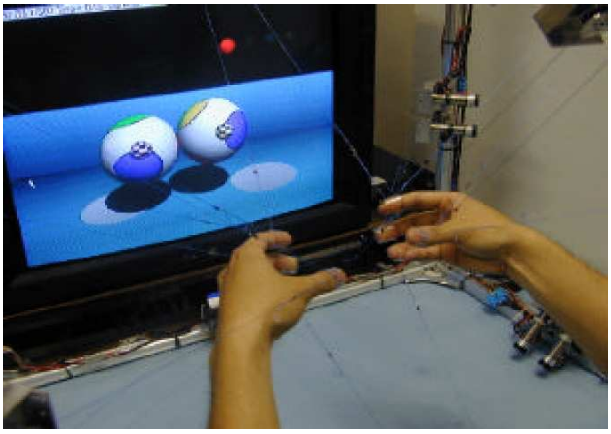

Figure 4.5: SPIDAR haptic device

(from [238])

vices, however, is not available, and (to the author's knowledge) have not yet been evaluated within the surgical simulation arena.

4.2 Characterising tissue behaviour

4.2.1 Viscoelasticity

Biological tissues are highly viscoelastic in behaviour [166]. This property requires that the stress at any time is made dependent not only upon the current strain, but also upon the history of the deformation. The simplest viscous material is known as the *Newtonian* viscous fluid [131], where the stress tensor (σ) is proportional to the strain rate ($\dot{\epsilon}$), that is:

$$\sigma = \eta \dot{\epsilon} \tag{4.1}$$

It should be noted that the simulator literature contains a certain amount of abuse of this concept. In truly *viscoelastic* materials, the phenomena of *creep* and *relaxation* play an important role in assessing the relationship between states of strain (deformation of the body) and stress (the distribution of force throughout the body) and behaviour becomes *non-linear.* For clarity, therefore, the following definitions are offered for viscoelastic materials:

- *creep:* if a body is suddenly stressed and then the stress is maintained constant thereafter, the body continues to deform.

- *relaxation:* if a body is suddenly stressed and then the strain is maintained constant thereafter, the corresponding stresses in the body decrease with time.
- *non-linearity:* the behaviour of linear systems is described in Chapter 6. It will be seen that these systems can be described by the relation $K\mathbf{u} = \mathbf{f}$, where K is the 'stiffness' matrix dependent upon the composition and geometry of the body under consideration (see Equation 6.38 for definition of these terms). An important distinction between linear and non-linear systems is that for the latter, K must be recalculated at each time-step, depending on the previous history whereas K is constant for linear systems [106].

Given the demands of real-time display, it should be noted that for most simulations non-linear behaviour is ignored. A few prototypical systems are nevertheless described in Section 4.5.

4.2.2 Tissue properties

4.2.2.1 *Approaches*

In vascular procedures, surgical experience suggests that tissue resistance can vary significantly, especially if vessels are diseased or calcified. In such cases, sufficient force must be applied at an appropriate rate - or the needle cannot be properly inserted. Some progress has been made with the application of viscoelastic models to medical simulations, where the number of degrees-of-freedom (dof) is restricted [467, 437, 86], but for more open applications, their use is prohibited [242].

The calibration of soft tissue models is the subject of ongoing work by numerous researchers [164, 436], but most recently (with respect to surgical simulation) at VESTA [27]. This work shows that the tissue stress response tends to follow a 'J'-shaped curve, with two possible phases of linearity, see Figure 4.6. This figure plots the reaction of *in vivo* porcine tissue against the Lagrangian stretch ratio, λ, where $\lambda = length/original\,length$. Attempts to measure the moduli of human tissue remotely are underway [164, 261, 402] (and see below).

Raghavan *et al* proposed a possible mathematical basis for the appearance of this curve, suggesting that the two linear phases correspond to the varied reaction of elastin and collagen fibres [327] (and see [271]). In their model, the elastin fibres react first, but are more compliant giving rise to the shallow initial portion of the

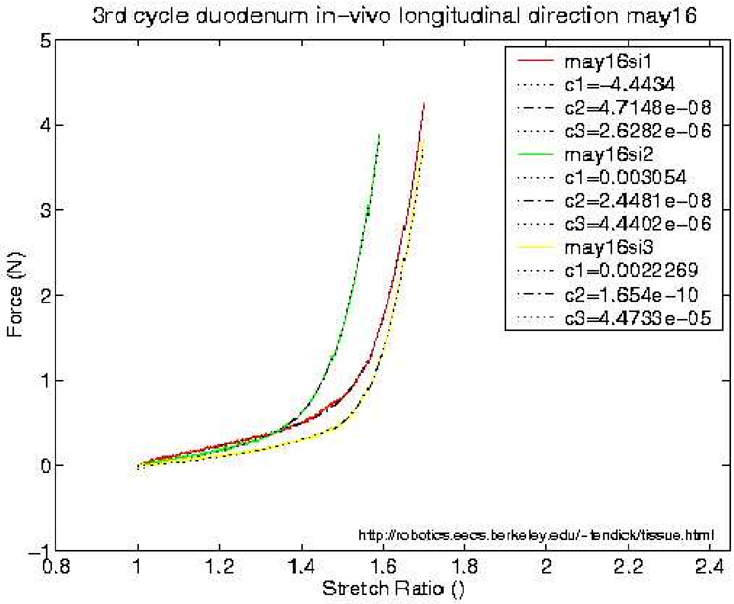

Figure 4.6: ‘J’-shaped tissue responses

(from [77])

strain curve. If the tissue is stretched further, the stiffer collagen fibres start to align causing a much steeper (and tougher) response. Eventually the collagen fibres come to dominate the response, giving rise to the second linear phase. Researchers at VESTA have shown that the initial phase of linearity may extend up to *c*.15% strain for *in vivo* tissues. For conditioned *ex vivo* tissues, this limit occurs at *c*.60% strain [77].

It is apparent from these results that choosing simple models to characterise tissue across a broad range of conditions is unlikely to give universal satisfaction. Configuring such models with appropriate parameters adds yet another layer of difficulty and numerous techniques for establishing these parameters both *ex vivo* and *in vivo* have been attempted [149, 245, 261, 326, 436, 460]. Fu *et al* [164] have observed that the most accurate numerical simulations of biomechanical problems employ estimates of Young's Modulus, E, for soft tissues in the range, $E = 1 - 200\,kPa$ and for Poisson's Ratio, $\nu \geq 0.495$ is usually employed. Choice of the latter is more restricted since $\nu = 0.5$ is the strict upper limit for incompressible materials at which conventional linear systems become insoluble. More difficulty arises if disease needs to be considered: Carter *et al* found that the right lobe of human liver had a mean elastic modulus of about 270 kPa — but a single case of a diseased liver had a modulus of 740 kPa [90]. Solutions to the choice of parameters for particular models will inevitably involve a quantity of subjective testing since function, scale, dessication and disease will all play a role.

4.2.2.2 *Assessment techniques*

Many recent studies have been orientated towards the validation of relatively new techniques of assessment, such as elastography [354]. Dimitriadis *et al* [137] have attempted to address a number of problems that limit the use of the atomic force microscope when measuring elastic moduli of soft materials at microscopic scales, by producing error corrections and obtaining estimates for sensitivity to error. Similarly, Nightingale *et al* have presented results from ongoing human *in vivo* and *ex vivo* studies, evaluating the correlation between acoustic radiation force impulse images and tissue pathology by use of eg. finite element models [301].

Vessel hardening has been investigated by Katakami *et al* [227] by employing ultrasonic backscatter to estimate the thickness of carotid artery intima media. Ebenstein *et al* [141] have described another force technique, using nanoindentation, which showed that repair tissue of rabbits possessed a much reduced modulus, despite being histologically comparable to undamaged tissue. *In vivo* human measurements have also been obtained by Herrington *et al* who used a computer-controlled air plethysmograph (in conjunction with MRI data) to identify the onset of atherosclerosis by estimating blood volume in the leg [204].

4.2.2.3 *Validation of tissue parameters*

The validation of particular tissue parameters for use in haptic simulations remains a relatively new field (but see 2.4.2.3). However, a study undertaken by Sur *et al* [404] found that a small group of registrars were reasonably sensitive to changes in Young's modulus (of *c.*1kPa) and Poisson's ratio (of *c.*0.02). But although most participants selected acceptable values for tissue parameters (when asked to choose), opinion was observed to vary quite widely as to what felt most 'realistic.' Further attempts to validate particular models are described in Sections 4.3.3.4 and 4.3.4.6.

An interesting approach which is still being developed is that of the 'truth cube.' Kerdok *et al* [231] took CT images of a cube of silicone rubber embedded with a regular array of Teflon spheres, which underwent various uniaxial compression and spherical indentation tests. This resulted in a complete set of volumetric displacement data which were contrasted to a finite element model using the same material properties, geometry and controlled boundary conditions. The data are offered as a 'proof of concept' for physical standards in validating soft tissue models and have been made available on the web (http://biorobotics.harvard. edu/truthcube). Future work is intended to develop a liver model.

4.2.3 Tissue response in surgical procedures

4.2.3.1 *Force analysis*

In parallel with attempts to characterise tissue in standard laboratory tests (ie. *in vitro*), several groups have attempted to investigate the forces and deformations involved with particular surgical procedures. For example, Azar *et al* have used a non-linear Mooney-Rivlin FEM to predict the position of possible tumours during breast biopsy [43]. Similarly, after Bholat *et al* [60] established that force-feedback was important for some laparoscopic procedures, other researchers have attempted to model the subtle forces involved [86, 311, 337].

Kitagawa *et al* [236] have analysed forces used in knot-tying in comparison with a telerobotic device. Interestingly, a test between novices and experts revealed that forces used during hand ties were significantly different between the groups (direction not given), but that these differences were lost when using robotic assistance.

4.2.3.2 *Puncture analysis*

Several attempts have been made to characterise the response of skin and muscle to puncture by needles. Brett *et al* [70] used a tensile testing machine to map the resistance force to hollow spinal needle placement during lumbar puncture. Higher needle velocities were found to result in lower peak forces encountered during the puncture of ligament. Ankersen *et al* [38] observed that skin is composed of two main layers: the outer epidermis and inner dermis. Most of the material strength of skin is provided by the dermis, which is made up of densely packed collagen fibres at random orientations, elastin fibres and a ground substance. This dual-layered structure causes skin to be supple at low strain but to exhibit considerable stiffness at higher strains. Despite this, the influence of the two distinct layers was not visible in the data of either the Brett or Ankersen studies.

More recently, however, Frick *et al* [161] were able to observe two peaks in the puncture data corresponding to the piercing of each layer in turn, Figure 4.7. In their study, samples of ovine skin and tendon material were pierced with straight

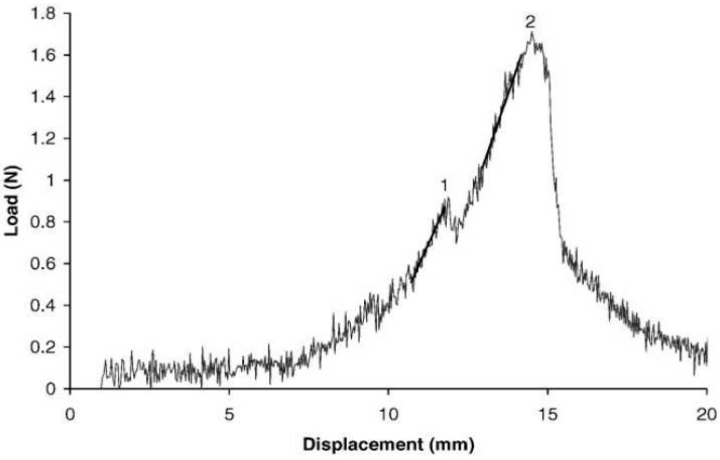

Figure 4.7: Load vs displacement of ovine skin

(from Frick *et al* [161])

suture needles under three different states of tension and with three different needle velocities (1, 5, and 10 mm/s). In contrast to Brett *et al*, no variance of tissue stiffness (the gradient of the graph in the figure) was found with needle velocity, albeit the statistical power of this test was low ($0.1 < \beta < 0.5$). The various states of tension were intended to mimic the action of surgeons steadying tissue prior to needle insertion; two surgeons were asked to provide an initial estimate of appropriate forces and the experiment was designed around these values. Tissue stiffness was found to vary significantly with respect to tensioning of the tissue prior to puncture, indicating that by increasing the level of control placed upon the tissue, a greater insertion force was required. In conclusion the authors noted that their study was: 'limited in that only one needle design, two sheep tissue types and three test displacement rates and tissue tensions were used. Results may differ with other needle displacement rates, designs and tissue types.'

4.2.3.3 *Modelling approaches*

It is convenient at this point to give a brief description of recent attempts to assimilate this behaviour into mathematical models for simulation. Direct measurement of needle forces is a challenging problem since soft tissues may both deform and move. DiMaio *et al* [136] have used the results of robotic testing, using an epidural needle with a tissue phantom ($E = 34\,kPa$, $\nu = 0.34$), to obtain estimates of the force distribution along the length of the needle during insertion. This allowed an improved model of insertion to be developed as the impact on the mesh was more controlled and regions of very high strain (which tended to exceed linear finite element capabilities) were avoided.

Alterovitz et al [35] observed that this model achieves fast update rates and high levels of accuracy, but requires a calibration phase which would be difficult to perform *in vivo*. An alternative model was therefore proposed, which was based on a reduced set of scalar parameters such as needle friction, sharpness and velocity. Using a nonlinear 2D finite element model, the authors found that a reasonable approximation to tissue behaviour could be obtained by considering the procedure (brachytherapy) as comprising seven phases of force interaction, eg. membrane puncture, insertion, tissue settling etc. The resulting simulation was capable of 24 frames per second rate using a 1250 triangular element mesh and therefore gave a usable real-time graphical representation.

A number of force display models have been recently developed. Okamura *et al* [306] proposed a 3-stage model, combining an initial nonlinear spring model, a modified Karnopp friction model and a constant cutting resistance for a given tissue. Data on needle diameter and tip type were also obtained using a silicone rubber phantom. However, a more dynamic friction model has been developed by Zhang and Phillips [461] to avoid the issue of criteria selection and the problems this creates when simulations approach these values. With the ultimate objective of validating such models, Healey *et al* [202] have obtained data from interventional radiological procedures, both *in vitro* and *in vivo*, by using non-intrusive finger-mounted force sensor pads. These data were calibrated against puncture force measurement apparatus. Although force, rather than pressure effects, were isolated, it was not yet possible to distinguish cutting from friction or damping effects. Interestingly, the patient's pulse created an additional level of 'noise' and it was suggested that this might be used to add or test realism in future simulators.

4.3 Deformable modelling in real-time

4.3.1 Overview

Deformable modelling for tissue simulation has shown three main axes of development, Figure 4.8. These axes can be described as:

1. Non-physical, including web-based systems with compositing or 'chainmail'

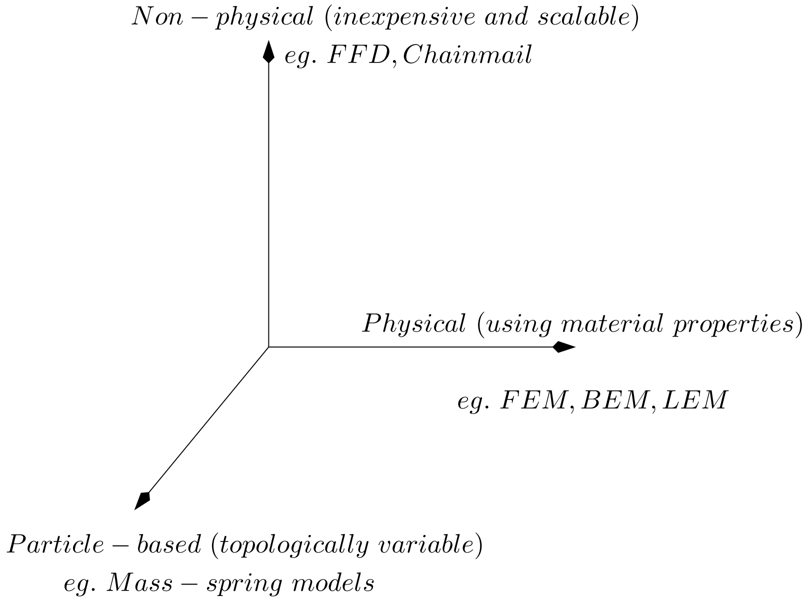

Figure 4.8: Axes of modelling development

algorithms: deformation characteristics are accumulated across the volume using, say, volume or greyscale intensity to estimate likely responses.

2. Particle-based, using mass-spring-damper (MSD) components to represent a continuous mesh structure. This model may be physically sophisticated, but in representing specific materials or tissues, the choice of parameters is arbitrary.
3. Physical, such as FEM, which uses continuous functions to represent known material properties.

In practice, simulations may use a mixture of models, depending of the requirements of the given task or sub-task (see 2.4.2.3). The development and orientation of these models along the suggested axes is discussed below.

4.3.2 Non-physical models

4.3.2.1 *Free-form deformations*

The earliest attempts to generate real-time (graphical) frame rates with deformable models used the surface-based geometric forms, the animation of which was achieved by manipulating the nodes of the mesh or outlying control points [371, 416]. Whilst these models were straightforward to implement in real-time, the absence of internal properties meant that it was difficult to create realistic deformations to simulate interaction. In other words, the simplicity of these models was offset by the skill required by designers to animate the meshes. Cover *et al*, for example, developed a laparoscopic simulation of a gall-bladder combining free-form deformations (FFDs) with energy-minimising 'snakes' to represent the impact of the procedure. These models could be convincing, although lattice violations and 3D aliasing were still common [114, 249].

Following improvements to the FFD algorithm to allow better volume preservation characteristics [207] and more intuitive methods of mesh manipulation [214], interest in the free-form approach has recently been revived. Several commercial 'low-cost' procedural simulators have been developed eg. by [**?**], including laparoscopic, catheterisation and suturing devices.

4.3.2.2 *Volumetric approaches*

Besides reducing objects to their surface geometry, another promising approach was to build simple 3D meshes (eg. of cubes) over which given properties could be accumulated. Avila and Sobierajski [42] created a voxel-based model which used image intensities (and intensity gradients) to propagate stiffness factors across the mesh. Forces could then be generated to allow the haptic exploration of visualization abstractions such as isosurfaces.

In developing the 'chainmail' algorithm, Gibson *et al* [175, 176] realized that deformation information could also be propagated efficiently across the volume, Figure 4.9. The low computational overhead of this scheme readily allows topological changes (eg. cutting) to be simulated and the method has proved sufficiently durable that various extensions have been established, such as: (i) a relaxation step, to provide a method of calculating force feedback [174, 162]; (ii) use of non-uniform grids and tetrahedral meshes [253] (see Figure 4.10) ; and (iii), accommodation within web-based simulations [254].

Although web-based applications achieve versatility through their availability and scalability, haptic feedback in this environment is not yet feasible [75, 222]. A prototypical arthroscopic haptic simulator using a PHANToM device was demonstrated in [174], which used a voxel-based method similar to that of Avila and Sobierajski (*ibid*) to generate force data from images of MRI data. Nevertheless, more direct methods of generating force-feedback are currently being investigated [98], with creeping, hysteresis and non-linear responses also being modelled [97].

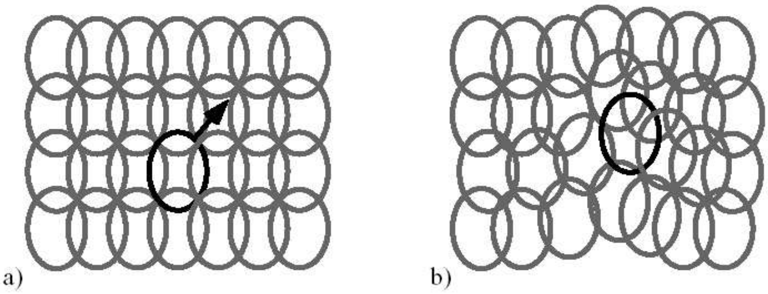

Figure 4.9: 2D Chainmail operation

In 2D, the Chainmail algorithm acts so that when one link of the 2D object is moved along the path of the arrow (a), its neighbouring links move to satisfy maximum and minimum distance requirements between elements (b) [174].

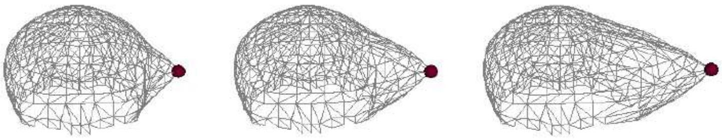

Figure 4.10: Generalised chainmail

(from [253])

4.3.3 Particle-based models

4.3.3.1 *The underlying physical basis*

This approach to modelling might best be described as 'quasi-physical': although the underlying mathematics has a basis in classical physics, it does not aim to represent material properties directly. Instead, deformable bodies are approximated by a collection of point masses connected by weightless springs, which are usually damped to control vibration. Real-time computation and topological changes are easily achieved for relatively large models, although subjective testing and an initial processing step is usually required to optimise the choice of parameters [325, 212]. The success of mass-spring systems is governed by [131]:

- *Topological design:* since springs are used to constrain the distance between two vertices, the number of springs per vertex conditions the global behaviour of the system. If the system is under-constrained, several rest positions are possible and the system can fall into unwanted local minima. If the system is over-constrained, the range of deformation is restricted.

- *Validity of deformations:* mass-spring models are not based upon continuum mechanics and cannot model deformations accurately beyond a very limited capacity. For small deformations, a spring model behaves similar to a linear elastic finite element model as verified by Keeve *et al* [229], but the two methods cannot otherwise be easily compared.

- *Dynamic behaviour:* for dynamic spring models (see 4.3.4.2 for a mathematical definition), there is a critical stiffness above which the numerical system is divergent (insoluble). This is also true for explicit linear FEM, but in practice, greater timesteps appear to be possible with the latter. This suggests that the range of possible dynamic behaviours is more restricted with mass-spring models (eg. they must be softer).

Deussen *et al* [135] used simulated annealing to search for optimal parameters. Another approach, favoured by Radetzky *et al* [324], has been to obtain expert input assisted by a *fuzzy-logic* procedure. This used natural language so that eg. 'consistency' was defined by the terms: *solid, hard, soft, wobbly, doughy, mushy.* Despite these drawbacks, numerous commercial systems (eg. [74, 243, 307]) and research prototypes (eg. [145, 193, 192]) have been developed using these models.

4.3.3.2 *An example MSD algorithm*

Brown *et al* [80] have offered the following description of their dynamic MSD algorithm. The geometry of a deformable object is represented by a 3D mesh M of n nodes N_i $(i = 1, \ldots, n)$, connected by links L_{ij}, $i, j \in [1, n]$, $i \neq j$. Each node maps to a specific point of the object, so that the displacements of the nodes describe the deformation of the object. The nodes and links on the object's surface are triangulated, whereas the other nodes and links are unrestricted, though it is often convenient to arrange them in a tetrahedral lattice. The mechanical properties of the object are described by data stored in the nodes and links of M. A mass m_i and a damping coefficient c_i are associated with each node N_i, and a stiffness k_i is associated with each link L_{ij}. The internal force between two nodes N_i and N_j is $\mathbf{F}_{ij} = -k_{ij}\Delta_{ij}\mathbf{u}_{ij}$, where $\Delta_{ij} = l_{ij} - r_{ij}$ is the current length of the link minus its resting length, and $\mathbf{u}_{ij}$ is the unit vector from N_i to N_j. The stiffness k_{ij} may be a constant or a function of Δ_{ij}. In either case, $\mathbf{F}_{ij}$ is a function of the coordinate vectors $\mathbf{x}_i$ and $\mathbf{x}_j$ of N_i and N_j. At any time t, the motion/deformation of M is described by a system of n differential equations, each expressing the motion of a node N_i:

$$m_i\mathbf{a}_i + c_i\mathbf{v}_i + \sum_{j\in\sigma(i)} \mathbf{F}_{ij}\left(\mathbf{x}_i, \mathbf{x}_j\right) = m_i\mathbf{g} + \mathbf{F}_i^{ext} \tag{4.2}$$

where $\mathbf{x}_i$ is the coordinate vector of N_i, $\mathbf{a}_i$ and $\mathbf{v}_i$ are the acceleration and velocity vectors respectively, $m_i\mathbf{g}$ is the weight of each node and $\mathbf{F}_i^{ext}$ is the total external force applied to N_i. $\sigma(i)$ denotes the set of indices of the nodes adjacent (connected by a link) to N_i in M.

Dynamic and quasi-static versions of this algorithm were developed. The dynamic model uses classical numerical integration techniques such as fourth order Runge–Kutta to solve Equation 4.2. For the quasi-static system, which was said to give reasonable performance in most simulations, the dynamic inertial and damping forces are ignored and the shape of M is defined by a system of equations expressing that each non-control node N_i lies in static equilibrium, according to:

$$\sum_{j\in\sigma(i)} \mathbf{F}_{ij}\left(\mathbf{x}_i, \mathbf{x}_j\right) - m_i\mathbf{g} = 0 \tag{4.3}$$

Solving the system by the quasi-static (QSS) algorithm essentially has 2 steps. In the first step, residual force components are accumulated for each node using the left-hand side of the expression in Equation 4.3. In the second step, a conjugate gradient type method is used to adjust $\mathbf{x}_i$ according to the force accumulated in step 1. In their evaluation of QSS, using a fixed number of iterations for step 2, the authors noted that in models of 8000 nodes, the error was consistently held at about 10% of the magnitude of the displacement of the control node for all mesh sizes. Errors with this algorithm for topological changes were not evaluated.

It should be noted that the relation 4.2 does not describe viscoelastic behaviour as several authors, including Brown *et al* (see also [324]), appear to suggest — see Section 4.2.1. Non-linear behaviour can nevertheless be incorporated within an MSD framework, although computation for real-time (especially haptic) display is as not yet possible [243]. To give a corresponding viscoelastic form, it would be necessary to recalculate the spring constants at each time step, ie. k_{ij} would become $k_{ij}(t)$ and then re-integrate Equation 4.2 for each different value.

4.3.3.3 ***Suture and knot-tying***

Several groups have used mass-spring based spline models to represent suture thread, though none of these have been integrated into full surgical simulation. LeDuc *et al* [247] explored several key principles for inserting and pulling thread through tissue. Their solution required the use of ‘home springs’ to return the mesh to its original topology and multiple velocity constraints to simulate the effects of friction. Lenoir *et al* [251], however, have modelled friction directly using constraints given by Lagrange multipliers and a two-stage integration process. Phillips *et al* [314] have also used splines to simulate knot-tying. Stability of the mesh was found to be improved by using Stoermer’s approximation for the second integral and hysteresis-like threshold to add or delete control points to conserve momentum (and to allow a simple node-based method of collision detection). This study appears to show that realistic knots can be stable within a VR environment without the need for complex friction models.

Mass-spring models are the basis for a number of laparoscopic suturing models, previously discussed in Section 2.3.2.

4.3.3.4 ***Recent research***

Maciel *et al* [264] have proposed various generic methods of obtaining spring constants in order that stable MSD systems can be constructed, sufficient to represent soft tissues and bone (which may be highly anisotropic). The best results were obtained by using an iterative method to determine the spring configuration, although this was not always satisfactory. In particular, this method required that moduli were tested in a preset direction and even then was occasionally unstable. Mosegaard, however, has suggested that optimal parameters will be found when models behave 'most alike.' An evolutionary algorithm was proposed, in which the *fitness* of the mesh was assessed by evaluating the extension of the springs compared with a reference model during the period required for the mesh to return to equilibrium. A static finite element model was chosen as the reference which, although slower, always returned to its undisturbed state. Mass-spring systems, on the other hand, reacted considerably faster but did not reach absolute equilibrium [288].

Mosegaard and Mosegaard *et al* [287, 289] have also attempted to build a cardiac simulation, comprising many thousands of nodes, suitable for pre-operative planning (without haptics). The initial proposal adapted the LR algorithm of Brown *et al* [79] and the relaxation technique of Casson and Laughier [91] to cope with a 35000 node model developed from MRI data, at least in the area local to tool interactions. More recently, however, the authors have found a considerable speed-up of processing time by transferring the problem to the graphics processing unit (GPU) of an nVidia graphics chip ie. by adopting a hardware-based solution. The initial obstacle to this conversion was the translation from 3D model to 2D textures, but having resolved this the authors have found a 30-fold decrease in solution times for models of up to 10^5 nodes.

A further interesting development is the development of 3D warping techniques combined with depth-mapping to overlay mass-spring models with photo-realistic images [146, 147], see Figure 4.11.

4.3.4 FEM

4.3.4.1 *Background*

Finite element models describe a given shape as a set of basic elements (triangles, tetrahedra, cubes etc.) where shape functions with limited support ('region of influence') are defined. This leads to continuous representations with varying levels of continuity [131]. In solid mechanics, this mesh is used to provide 'elements' upon which the elastic material functions of stress and strain are integrated. This requires considerable computation, which for many engineering applications is usually important, but not critical. In comparison with mass-spring systems, the method gives a much clearer representation of tissue parameters to assess forces and damage and the accuracy of the model can much more readily be upgraded by increasing

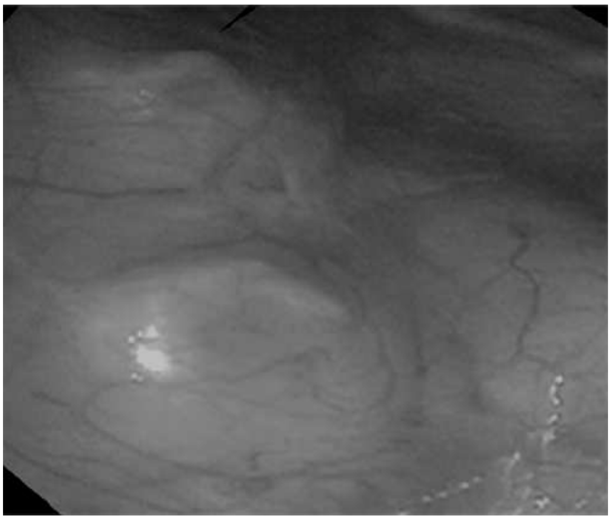

Figure 4.11: 3D Warping technique of ElHelw *et al* [147]

the number of elements. Furthermore, the technique is readily extended to more complex models of tissue behaviour such as anisotropy [315].

4.3.4.2 ***Mathematical basis***

A mathematical basis for linear tetrahedral finite elements using the principle of *virtual work* is developed in Chapter 6, but the general governing equation can be stated as:

$$M\ddot{\mathbf{u}} + D\dot{\mathbf{u}} + K\mathbf{u} = \mathbf{f} \tag{4.4}$$

where $\mathbf{u}$ is the displacement vector, $\mathbf{f}$ is a vector of forces/boundary conditions and M, D and K are (respectively) mass, damping and stiffness coefficient matrices.

For dynamic systems, where M and D are non-zero, a major difficulty consists of ensuring *synchronicity*, ie. that the numerical time used for computation matches the user's time for interaction. When calculating the velocity of vertices, for instance, we need to know the time interval very precisely to divide the difference in displacements at the current and previous timesteps (these quantities may be very small so that errors are magnified). Static equations, where Equation 4.4 is reduced to $K\mathbf{u} = \mathbf{f}$, cannot be used to model inertia or viscoelastic properties, but have two computational advantages [131]:

- They are faster to compute since no time integration step is needed.

- They are well-suited to parallel or asynchronous algorithms. Cotin *et al* [111], for example, used a static formulation of motion which allowed the decoupling of force and deformation computations.

4.3.4.3 *Early applications (not real-time)*

In 1994, Sagar *et al* [351] developed a virtual environment for eye surgery simulation where the cornea deformation was modelled as a non-linear elastic (Mooney-Rivlin) material. The finite element solver computed the cornea deformation every second while the graphics module was able to provide a 10Hz refresh rate, which was unique at that time. Another typical early application of FEM to surgical problems was that of Keeve *et al* [229] who, in 1996, used the method to predict the outcome of facial surgery. These simulations could be computed very quickly (in the order of a few minutes), but were not intended to run in real time.

4.3.4.4 *Real-time approaches*

The emphasis of much FEM research in this field is upon finding faster solutions. Shiakolas [385], for example, proposed a closed form method of computing stiffness matrices although this method has not been adopted in simulations as far as the author is aware. *Condensation* and *Banded-matrix* methods developed (respectively) by Bro-Nielson *et al* [71] and Berkley *et al* [58] use matrix manipulations to remove the need to compute the influence of internal nodes (see discussion in Section 6.3.2). This meant that real-time solutions became possible albeit substantial pre-processing steps were then required. The need for significant pre-computation was a limiting factor, however, since this prevented further topological changes of the mesh, such as might be required to represent tearing, cutting or piercing.

Cotin *et al* [112] presented a more radical solution, the *tensor-mass* model, using an extensive pre-computation step compiling tensors to define standard displacement fields at each movable node in the mesh. This work was based on the principle that linear static elements define regions of constant strain and since elastic energy may be expressed as a quadratic function of displacement, the force at each node can be defined as a linear function of displacement. Using a conjugate gradient solver and a restricted collision detection algorithm (see 4.6.3), the tensors and mesh can be updated dynamically, allowing topological changes (such as cutting) for meshes of 760 nodes with updates at 40Hz (on 233MHz PC) in a hepatic (liver) simulation. Also, with super-imposed solutions, non-linear models could also be approximated

[113]. More refined algorithms for achieving cutting/tearing are discussed below (4.3.4.5).

Ignoring cutting operations, several FEM implementations using matrix factorisation have been shown to be feasible:-

- James and Pai [219] have produced interactive linear elastic simulations by using boundary integral formulations (ie. *Boundary Element Method* or *BEM*) for graphical character animation. The authors point out that BEM produces smaller, more compact linear systems which are therefore easier to solve; also, BEM is more accurate for computing contact forces than the FEM since forces are solved for just like displacements, instead of being derived from displacements using difference formulas. But since the influence of internal structures is ignored, only homogeneous materials may be considered ie. variations due to anatomy or disease cannot be modelled. Also, as the technique is best suited to rounded objects, haptic interaction with more realistic human anatomical models has yet to be achieved [459] (and see [279]).

- The method adopted by James and Pai in the above is an algebraic procedure which is more or less equivalent to computing a matrix inverse [131]. James and Pai have, however, extended the technique to solve linear elastostatic systems by using pre-computed Green's functions (GF) and fast low-rank updates based on capacitance matrix algorithms [220]. The matrices constitute exact force response models, allowing contact forces to be computed much faster than global deformation behaviour. It is also possible to decouple the global deformation calculation from that of the local force response, so that for haptic displays, the local contact response may be computed at a much faster rate than the global deformation. The authors have demonstrated satisfactory haptic performance for modest models (<1000 nodes) using Java3D and a native interface to the GHOST API [373]. Collision detection, however, was limited to a single contact point on the undeformed object. A similar approach has also been adopted by Nikitin *et al* [302].

- Zhuang and Canny [463] observed that linear strain does not model finite rotation correctly, and introduces distortions when large global deformations occur. Employing quadratic strain terms avoids this problem, but the authors found that implicit integration in real-time was impossible for meshes of any size (implicit schemes tend to have better convergence properties). However, by lumping the rows of mass matrix, M, into a diagonal form and adopting a form of Rayleigh damping (ie. taking $D \propto M$), it was possible to use an explicit integration method to obtain solutions for the nonlinear problem at above 30Hz for a mesh of a few hundred nodes.

- Székely *et al* have employed massively parallel hardware to produce a fully dynamic, non-linear simulation of endoscopic procedures [408, 409, 167].

4.3.4.5 *Tearing and cutting*

Several methods have been proposed to allow topological changes to finite element meshes in real-time. Bielser and Gross [62] used pre-defined splitting paths to create smooth edges. This method guaranteed 17 extra tetrahedra for each split tetrahedron and was therefore viewed as expensive (although this was later refined [61]). Nienhuys and van der Stappen, therefore, performed 'cuts' along faces of the mesh using a heuristic for determining which faces to cut. Nodes within the mesh were relocated to align the mesh with a virtual scalpel and prevent a jagged surface appearance (any degeneracies were later removed) [299, 300]. Using an optimised conjugate gradient solution, the authors obtained interactive frame rates (graphical) for a mesh of around 1500 nodes, see Figure 4.12 .

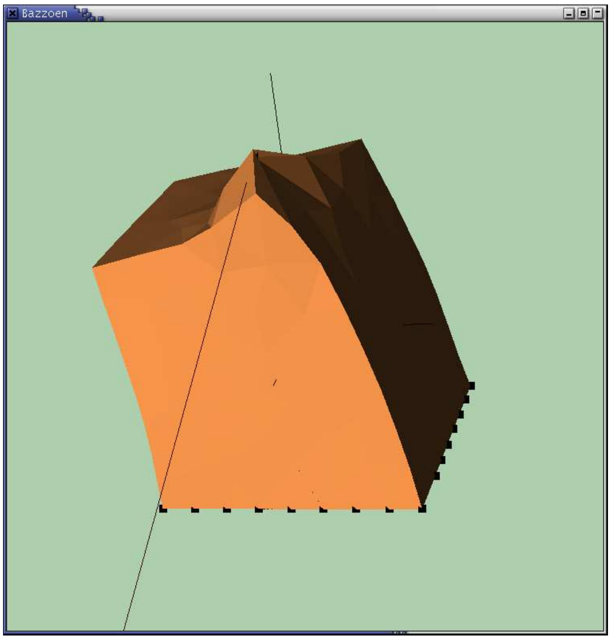

Figure 4.12: Interaction with Bazzoen FEM cube

(from [298])

In future, the answer may lie in the realm of so-called meshless methods. De *et al* [129, 128] have suggested that ordinary meshes should be abandoned in favour of a more localised systems of 'spheres', in effect allowing a locally refined mesh to be quickly constructed at the point of contact. Another suggestion is that by Vigneron *et al* [434]. By incorporating discontinuous functions into the standard FEM, the *Extended FEM* can be used to model incisions, without the need for remeshing. The choice of these functions was explored by the authors and a successful simulation was created using simple 2D objects (rectangles and ellipses).

However, a more immediate solution may be the use of multi-resolution, or hierarchical, meshes. In most simulations, the effects of tool interactions are relatively local to the point of contact, so it is generally safe to ignore the displacement of distant nodes. In the research by Faraci *et al* [152], contact results in the selection of tetrahedral nodes nearest the contact point ('level 1'), then those of the tetrahedra associated with these nodes ('level 2') and so on. Using a level 2 mesh, Rayleigh mass-lumping and pre-computed element volumes etc., the finite element equations may be set up and solved using a central differences scheme in real-time. This method is fully dynamic in that different parts of the mesh may be selected at each tool contact. Using a liver model with 1500 nodes, the authors were able to investigate the choice of various damping parameters and constraints for use with haptic simulation. The authors have also incorporated non-linear behaviour and mesh refinement (to increase stability) for meshes of the order of 10^2 nodes [153]. A hybrid multi-resolution model, capable of haptic update rates, has also been advanced by Frisoli *et al* [163].

4.3.4.6 *Recent research*

Zhong *et al* [462] have proposed an extension of the tensor mass model of Cotin *et al* [112] by pre-computing the matrix inverse and condensing to remove fixed boundary nodes. Whereas the former method requires that the FEM solver execute $3k$ times (where k the number of contact nodes), using the inverse allows the generation of tensor components directly. The authors have also described algorithms to introduce a polynomial interpolation of non-linear behaviour and an affine mapping of contact regions using St Venants Principle. A graphical simulation incorporating these ideas has been developed which allows limited interaction of brain tissue.

Kuroda *et al* have attempted to model interactions between multiple soft objects of different elastic properties [244]. This problem creates particular difficulties for collision detection algorithms, since the collision mesh must also be updated (see

4.6). The authors' solution to this problem was was to generate an approximate solution of temporary displacements from normal triangle intersections, which was then used to determine normal stresses for colliding bodies. This iteration then allows more accurate displacements to be computed and was found to be sufficient to generate haptic updates for a palpation simulation at 250Hz.

A similar problem exists where deformable tools must be used. As a first step, however, Bhat *et al* have developed a catheterisation simulator which combines rigid body dynamics with Euler-Bernouilli 3D beam formulation, which for the i^{th} beam, has the equilibrium equation:

$$\nabla^2 \left(EI \left(\nabla^2 u_i \right) \right) - f_i = 0 \tag{4.5}$$

where E is Young's Modulus, I is the moment of inertia of the section about the neutral axis, u_i are the displacements and f_i the contact forces. The resulting simulation did not model tissue deformation, but was able to provide a real-time graphical display [59].

4.4 Hybrid and volume-preserving approaches

Several research groups have proposed extensions to the methods described either by adopting hybrid models or by enhancements to perceived defects, notably volume loss. The hybrid approach is used in the KISMET laparoscopic system [242, 243], which appears to employ mass-spring models for 'cutting' operations and condensed static FEM where accuracy is needed. The nature of interaction between these models has not been published, however, since this is a commercial system.

In another approach, Tseng and Lin have extended the method of approximate FFD modelling (see 4.3.2.1), combining it with a mass-spring model, to create a real-time haptic laparoscopic simulation [425]. In addition, Hirota *et al* have extended the basic FFD algorithm to achieve volume preservation on highly refined meshes [207].

A more promising technique from this point of view is that of 'Long' or 'Radial' elements, in which artificially constructed long or radial elements are coupled with Pascal's Principal to reduce mesh complexity whilst guaranteeing volume conservation. Neither method requires any numerical scheme of integration or pre-computed condensation step and both methods have been successfully tested with haptic simulations of less than 1000 elements. One drawback, however, is that only appropriately shaped objects can be modelled [110, 46].

4.5 Viscoelastic simulations

A number of researchers have attempted produce more realistic tissue deformation by use of non-linear techniques either with purely graphical displays or with limited haptic interaction. Scilingo *et al* employed Hertz theory based on solids of revolution to create a non-linear response which was rendered by a 1D pneumatic haptic device [365]. Cai *et al* [86] employed an implicit Euler integration scheme in conjunction with a linear viscoelastic Voigt dashpot to generate non-linear behaviour for a small plate of *c*.500 nodes. This was linked to 2D haptic and graphical display and was capable of updates at 25 Hz (on a 450MHz PC).

Schill *et al* have extended the chainmail algorithm (see 4.3.2.2) to accommodate the behaviour of inhomogeneous materials [360]. The *Enhanced 3D Chainmail algorithm* works by processing the elements in the object so that the deformation travels most quickly through stiff materials. The intended application for this technique was to simulate a vitrectomy procedure (the removal of blood, debris etc. from the eye) but this does not seem to have been followed up. Later, however, Frisken-Gibson [162] was able to show that the method could be adapted to allow a relaxation step in which hysteresis-like behaviour could be incorporated. Hysteresis and creep were introduced into the model by Choi *et al* [98] which combined a force propagation approach with a mass-spring based mesh.

Mahvash and Haywood observed many researchers in this area ([86, 456] etc.) had essentially simplified either FEM or the contact problem to make the high rate computation of forces possible [268]. To address this, the authors developed an approach based on the book-keeping of force deflections curves stored at the nodes of a triangulated body surface. Using a virtual environment which comprised a tool interacting with a deformable cylindrical virtual body made of about 500 ‘patches’, their tests showed that coordinates interpolation, together with force-deflection interpolation provided continuity for the responses. The forces were generated by a PenCat/ProTM haptic device (Immersion Inc. [25]) which is ‘direct drive’ and hence provides good fidelity because of near absence of mechanical damping.

4.6 Collision detection

4.6.1 Background

Efficient collision detection has been the subject of a great deal of research over the past decade and many libraries have now been released into the public domain eg. VCollide [215], V-Clip [278]. Several groups have developed techniques specifically for rigid body haptic interaction. Koenig *et al* used coherence [239] to optimise the collision search. Gregory *et al* used tightly defined bounding boxes in HCollide [256]. None of these algorithms are capable of handling deformable models. For researchers working in this area, three possible avenues would seem to be open: (i) to update bounding boxes after deformations occur; (ii) to employ hardware-based optimisations; and (iii) to use a local collision detection scheme, with specific simplifications depending on the task.

At the time of writing, it is not possible to obtain a collision detection library which supports deformable models, either commercially or in the public domain[1]. As a result, many surgical simulations have developed in-house systems (ie. a local methods) eg. KISMET, BDI etc. The remaining options are explored briefly below.

4.6.2 Bounding-box techniques

van den Bergen has adapted the algorithm of Gilbert, Johnson and Keerthi (GJK), which essentially provides a simple, efficient method for finding the minimum distance between two convex objects [430, 177]. Axis-aligned bounding boxes were shown to be more efficient for handling dynamic and deformable models than arbitrarily oriented systems [429].

In [80], Brown *et al* pointed out that this scheme tended to produce an unbalanced tree hierarchy which was potentially more costly in terms of collision detection queries, and, more seriously, was unable to exploit the localised nature of most deformations. Instead, the latter favoured a sphere-based bounding box scheme (based on Quinlan's algorithm [322]) in which spheres of a set radius were allocated to each triangle in the mesh and a hierarchy of larger spheres defined the collision search path. This scheme has yet to be integrated into a full simulation, but the authors estimated that maintenance of the sphere-based collision tree required 0.06 ms per deformed triangle. Ganovelli *et al* have advocated a more flexible approach to the

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[1] SOLID [429] includes an appropriate API, but does not yet function correctly: see Section 5.3.6.

choice of bounding volume by using a selection step to optimise this choice [171].

4.6.3 Hardware solutions

The 'bucket' data structure created by Cotin *et al* (see 4.3.4.4) allowed effective allocation of surface triangles into separate bins but did not permit updates to the bucket data structure when running. But even if real-time updates were allowed, schemes of this type are scarcely adequate where large deformations and topological changes can — and often do — occur: time spent pre-computing complex bounding volumes appears to be fruitless. Also, since complex anatomical objects usually remain in close juxtaposition, collisions can be frequent and numerous.

Fortunately, the tools themselves can usually be modelled by simple shapes and their motion is quite restricted (at least in laparoscopic procedures), so that there is little difficulty in simulating the required workspace in modern, hardware-accelerated displays. For Lombardo *et al* [260], the pruning of distant triangles from the display frustum, and the availability of these routines through OpenGL, suggested a mechanism by which dynamic collision could be implemented. In particular, the authors found that by defining additional view volumes around these tools, it was possible to make OpenGL calls to obtain a list of nearby triangles. The view volumes could also be distorted to cover the region of movement around each tool over a given timestep. In addition to coping with deformable models, the scheme was at least 5 times faster for rigid body interactions than, for example, RAPID [14].

Hardware-based approaches using multi-pass rendering techniques to generate proximity queries have also been proposed by Hoff *et al* [208] with optimisations (by making direct calls to the graphics processing unit) by Govinderaju *et al* [185].

4.7 Applications to suturing

4.7.1 Overview

This section briefly reviews published modelling approaches of several prototype suturing simulators — the reader is referred to Section 2.4.3 for a discussion of the validation of these systems.

4.7.2 BDI anastomosis simulator

The BDI simulator modelled two tube-like structures comprising around 1200 polygons which were displayed through OpenGL accelerated hardware on a Silicon Graphics Maximum Impact Indigo 2 workstation. A lumped-mass model was used to model the 'free' vessel and an elastic spine was used to model bending, stretching and local deformations [318]. The physical properties of the tube, such as compliance, were set after discussion with a number of physicians. A simple damped mass-spring model (based on penalty-method techniques) was used to calculate forces, displayed using PHANToM devices from SensAble [373]. Collision detection was adapted from the method of Lin and Canny [255]: polyhedra were stored in memory as a series of depth values and compared with the 'depth' of the tool contact point.

The metrics used for validation are described in Section 2.4.3.3.

4.7.3 Penn State University/Millersville prototype

Webster *et al* [444] (see also Haluck *et al* [192]) have developed a haptic simulation designed to teach basic suturing for simple wound closure. A damped 2D mass-spring mesh (overlain by a wound texture) was employed to provide the underlying force model, see Figure 4.13 . Deformation computations were undertaken by using an implicit solver and speeded up for real-time use by using the pre-computational approximation method of Desbrun *et al* [134]. The stereo graphics display was enabled by a WildCat board using EAI/Sense8's WorldToolkit API of OpenGL calls [9]. Forces were rendered using a PHANToM force feedback device and GHOST from SensAble [373].

The device used real needle holders, which were attached to the PHANToM end effector with a contact switch to sense open/closed states. This allowed the development of a finite state model for suturing based upon the work of Rosen *et al* [346]. In the state model, the sub-tasks of each stitch were modelled as: *Idle, Grasping, Puncturing, Opening, Closing* and *Pulling through.* The system records the positions and orientation of the Phantom encoders and graphic objects (needle, sutures, needle driver) so that the user's suturing technique may be replayed for training purposes.

4.7.4 Stanford microsurgery simulation

Microsurgery is a well-established surgical field which involves the repair of approximately 1mm vessels and nerves under an operating microscope. Given the small

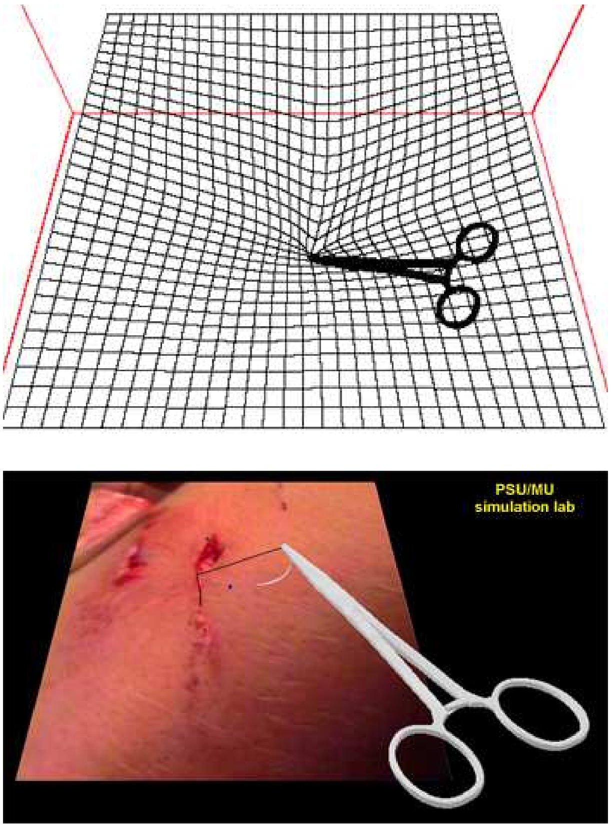


Figure 4.13: Penn State/Millersville prototype

(from [192])

sizes of vessels, forces are negligible and, consequently, were ignored for this simulation. Despite the development of a linear viscoelastic model to depict deformations, Brown *et al* [78] observed that a *quasi-static* model was both faster and sufficient (the algorithm for this model is described in Section 4.3.3.2). The setup for microsurgery included two real surgical forceps instrumented to detect closure, attached to electromagnetic trackers (miniBIRD, Ascension Technology Corporation [5]). Suturing was displayed on a stereo graphics system with updates at 30 Hz, see Figure 4.14.

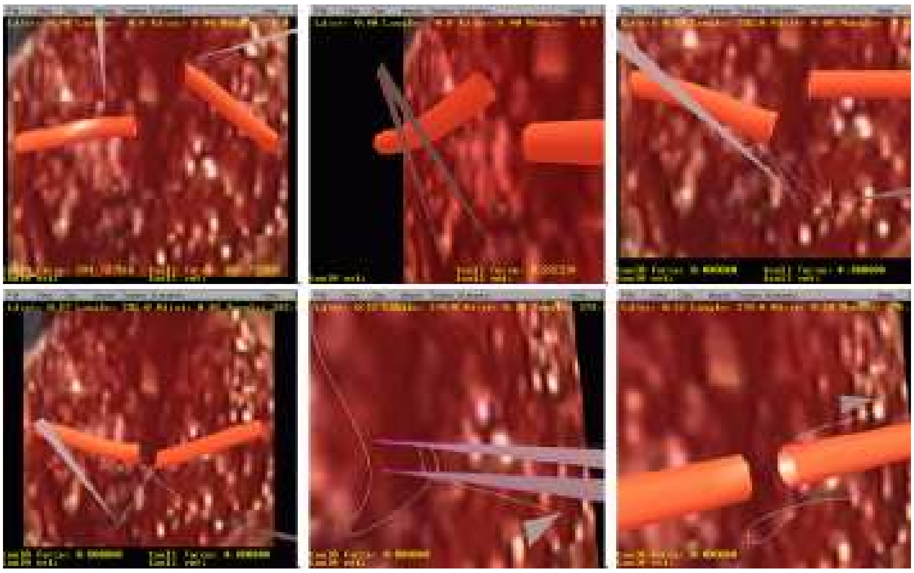


Figure 4.14: Stanford microsurgery system

(from [78])

The sphere-based collision detection algorithm for this system is described in Section 4.6.2.

4.7.5 Human Interface Technology (HIT) Lab simulator

The *banded-matrix* technique developed by Berkley [58] is discussed further in Section 6.3.2. This system employed stereo graphics with a PHANToM desktop device [373] and was oriented towards a simple wound closure of a hand model, see Figure 4.15. Many of the details relating to this system were not fully published as a commercial system is planned.

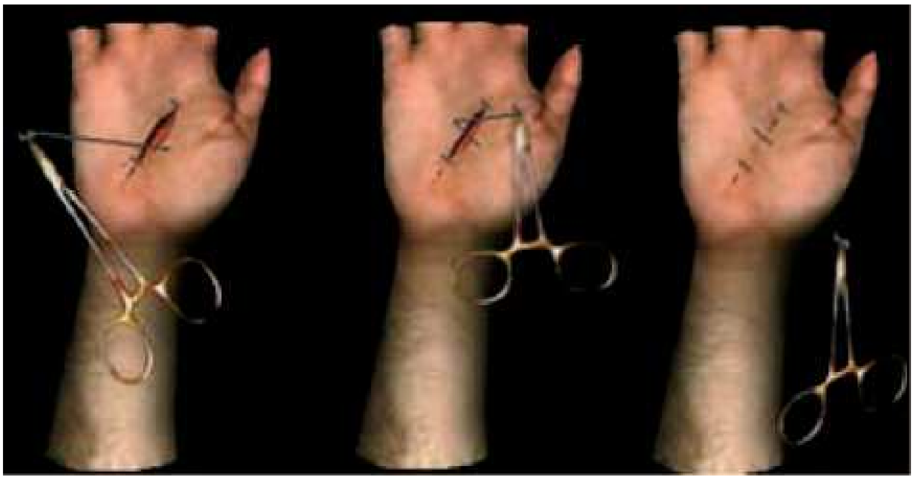


Figure 4.15: HIT Lab simulator

(from [58])

More recently, however, Lindblad *et al* [257] (also at the HIT Lab University of Washington, Washington, USA) have published proposals for a bimanual simulator based on interactive FEM. Currently, the system employs a simple model of quadratic triangular prism elements to compute reaction forces. For collision detection, the virtual forceps and needle driver are represented as single points of contact, and ray-triangle intersection algorithms are operated on separate threads for each tool, the forceps with a 'hit-and-stick' type model (which allows one thread to be suspended after collision). At present, forces are rendered with two PHANToM devices, but this is likely to be replaced in future with the planned commercial system. Berkley *et al* [57] have also recently published proposals for a 'fast finite element' simulator, which has a number of similarities to the system described in Holbrey *et al* [209] and the following chapter.

4.7.6 Recent research

Whereas a number of commercial laparoscopic systems have recently incorporated suturing modules (see 2.3.2), there appears to be little comparable progress in open surgical contexts. There has, nevertheless, been a good deal of work in the area of contact forces and tissue puncture (see 4.2.3) and several of these are appropriate for discussion here. The difficulty of representing forces during suturing, for example, has prompted Kitagawa *et al* [235] to investigate the use of compensatory feedback methods for daVinci system. Knot-tying by five experienced surgeons was tested under various feedback conditions: none, auditory and visual. Visual feedback was found to be most effective, although auditory information also provided some support.

Batteau *et al* [51] used CathSim (see 2.3.5.2) to present a needle puncturing task which allowed the authors to investigate user perception to effects such as haptic recall and latency. In first of two experiments, 27 volunteers (with a range of experience) were asked judge when the forces felt most appropriate after increasing the gain on the device over regular increments. The results revealed a very wide range in ability of the subjects to recall haptic events, which was uncorrelated with experience. In the second experiment, latency in the force feedback was gradually increased, and then decreased, to the level of the user's perception, generating low and high values of acceptable latency. The authors reported that a large proportion of the test population were unable to discriminate latencies of 54ms (19ms was the lowest value reported), suggesting that for some tasks, haptic update rates may be significantly reduced.

Lee *et al* [248] have presented a novel method of contact modelling between rigid surgical tools of arbitrary shape and deformable virtual organs bounded by triangular mesh surfaces. The authors used a 'divide and conquer' strategy, based on the minimisation of an energy function, to redistribute an arbitrary field of displacements onto virtual surfaces. The computational complexity was found to depend on the size of the touch field. Figure 4.16 gives an illustration of the results: the red arrows (left figure) indicate the applied forces, whilst the blue arrows (central figure) show the redistribution of force vectors onto nodes of the mesh.

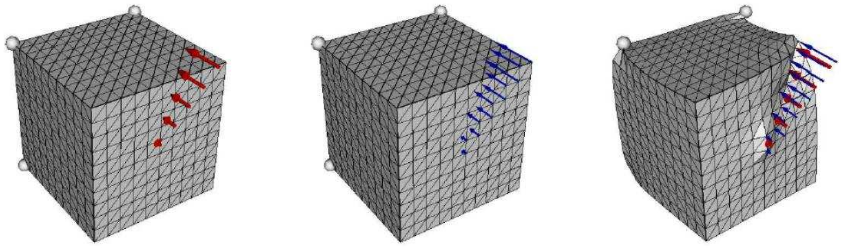


Figure 4.16: Redistribution of forces (from Lee *et al* [248])

Some new initiatives for the application and development of VR tools may also be mentioned here. Several groups, for example, have proposed open-source frameworks to help stimulate and combine research efforts, notably: Montgomery *et al* and *Spring* [81, 280]; and, Çavasoglu *et al* and *GiPSi* [92]. As far as the author is aware, however, analyses using these tools have yet to be published. In contrast, Ridgway *et al* have managed to reverse the usual trend by using ICSAD to assess the efficiency a new suturing technique [338].

Chapter 5

Design and Implementation

This chapter draws together ideas and elements of design from previous chapters with the objective of creating a usable training simulator. The first section describes a number of exploratory investigations using material obtained from CD-rom 'tutors' and observation of trainees and surgeons. Section 5.2 details the adopted design pattern in its basic form, and extensions suggested by other work reviewed. Section 5.3 discusses the current implementation along with hardware and interface issues which also had to be solved.

> 'I always say that nothing is to be done in education without steady and regular instruction, and nobody but a governess can give it.'
>
> - Jane Austen, Pride & Prejudice (c.1813)

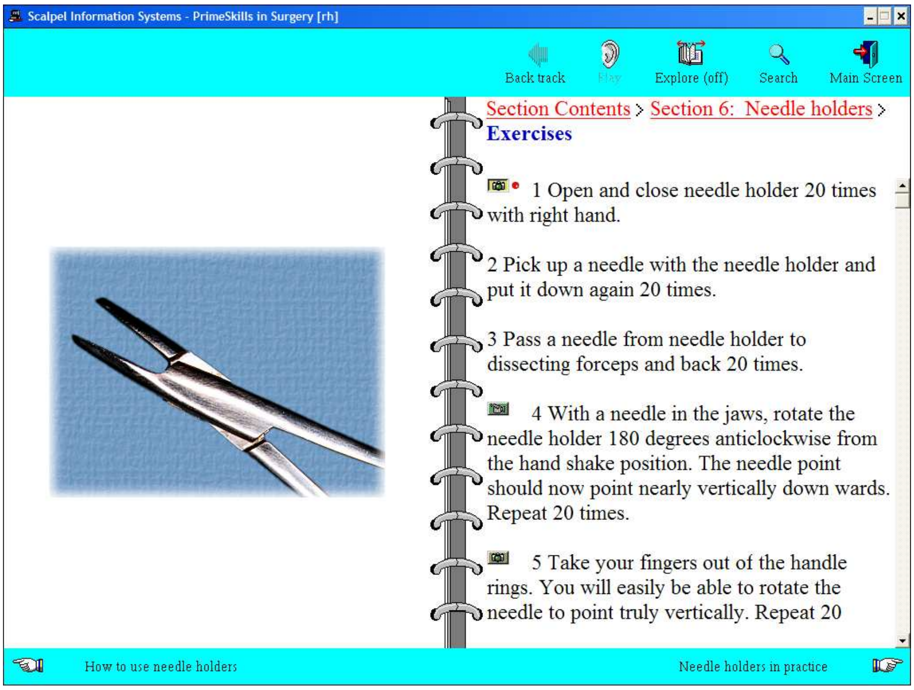
5.1 Preliminary investigations

5.1.1 CD-ROM tutors

5.1.1.1 *PrimeSkills in Surgery*

In 1996, Edwards and Trigwell wrote of the coming crisis in surgical training [143]: whilst surgical techniques were becoming more technically demanding and patients less forgiving, 'there is less time to train the junior surgeons, and less time to allow the juniors to do the operations themselves'. Recognising also that textbooks go out of date sometimes before publication, the authors proposed that new methods of tutoring were required. A further criticism of such texts was the lack of precision: quoted distances, for example, may be given as 'small' rather than, say, 4–5 mm. For surgical trainees, apprenticeships only aggravate this problem, since the consultant in charge of a procedure is usually too busy to be specific for their benefit [M. Edwards *personal communication*, October 2002].

To address these issues, the authors compiled a series of several training programmes in CD-rom format. The 'Prime Skills' CD [142] gives a book-like display with a schedule of key points about given procedures and related tools eg. Figure 5.1.



Section Contents > Section 6: Needle holders >
Exercises

1 Open and close needle holder 20 times with right hand.

2 Pick up a needle with the needle holder and put it down again 20 times.

3 Pass a needle from needle holder to dissecting forceps and back 20 times.

4 With a needle in the jaws, rotate the needle holder 180 degrees anticlockwise from the hand shake position. The needle point should now point nearly vertically down wards. Repeat 20 times.

5 Take your fingers out of the handle rings. You will easily be able to rotate the needle to point truly vertically. Repeat 20

Figure 5.1: Prime Skills schedule

(from [142])

For the present project, the clarity of the description for the use of needle holders was especially laudable. Three principal actions were described:

- *Rotation:* prior to inserting (or withdrawing) the needle, the surgeon uses a 'screw-driver' rotation to bring the needle into position, ideally at an angle of

90° to the tissue surface and to the orientation of the wound. The amount of rotation needed may be 180° or more.

- *Pressing:* this is often an unexpected requirement for beginners when learning to suture surface wounds. When needed, the surgeon must press firmly onto the tissue with the jaws of the needle holder so that space is created for the needle to enter. Failure to create adequate space makes the needle difficult to handle and may bend the needle.
- *Curving:* through tissue, movement of the needle is *not* a simple screw-driver rotation: the surgeon has to follow the curvature of the needle. A beginner who tries to rotate around the holding position may find that the needle will break.

Commenting on these programmes, Thomas [418] has pointed out that although suturing a jiffy bag was unrealistic, the didactic format with timed exercises was very suitable for junior trainees (some errors, notably in knot-tying and handling needles by hand, were also indicated). In a similar scheme, O'Connor *et al* [305] found that first year medical students trained for 3–4 hours on a computer-based learning module were indistinguishable from final year medical students in terms of an Objective Structured Clinical Examination[1].

5.1.1.2 *The Suture Tutor Kit*

To assist with the current investigation, the 'Suture Tutor Kit' was purchased from Limbs & Things (part no. 90024 [20]). The kit contained a synthetic skin pad, scalpel, forceps, needle driver, needle and a tutorial CD-rom. Advice on practising various stitch types and knotting information was presented, eg. see Figure 5.2. It is notable that for closure of surface wounds, as represented by the skin-pad, both hands must work in coordination, with the non-dominant hand in a supportive role. Use of the kit was made during later evaluation (Chapter 7) and the CD-rom was particularly valuable for examples of handling instruments correctly (see Appendix C).

Much more tutorial information is now available on the web at eg. [15, 19].

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[1] The authors cautioned that the first-year students were trained very close to the time of the examination and, as such, may have had an advantage; also, retention was not tested. Readers should also note earlier comments about misuse of the null hypothesis in Section 3.3.1.

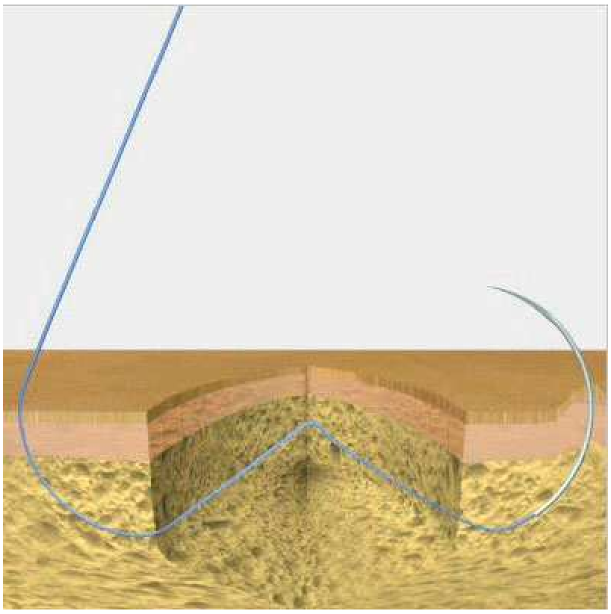

Figure 5.2: Curved suture path

(from [20])

5.1.2 Observation of surgical training/procedures

5.1.2.1 *Basic Surgical Skills training*

The author attended a 3-day course in Basic Skills Training (in a non-participatory capacity) at Leeds General Infirmary during 2002. Suturing and vascular anastomosis occupied approximately half of this period, although equal weight was given to performing well-tensioned suture-ties as handling tissue and placing sutures (most ties were practiced on an Ethicon® knot-tying board). Defrozen segments of pig aorta were the preferred medium for suturing, as synthetic substitutes were not thought to be adequate.

Longitudinal and end-to-end anastomoses were practised (Figure 1.1(a) and (c) respectively), both requiring considerable skill to provide access and control the tissue. For bowel anastomoses, a precise extra-mucosal technique was thought to be ideal (Figure 5.3). Here the needle perforates the bowel at the serosal surface, passes through muscle tissue and emerges between the sub-mucosal layer (the strongest layer in the vessel wall) and the mucosa. To assist with placing sutures, additional holding stitches (tensioned by clamps) were also used. Several recommendations

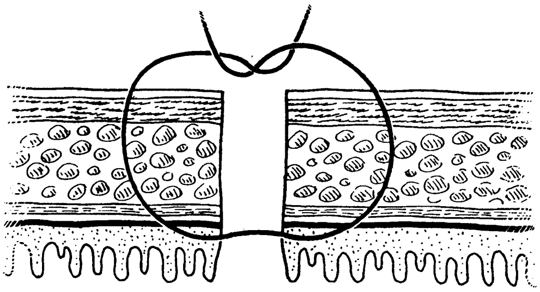

Figure 5.3: Extra-mucosal suture technique

(from [350])

were also made at the course including: (i) beneficial use of low-powered magnifying aids to focus on the area of the wound; (ii) development of 'palm' technique, in which the needle holders are held in the palm of the hand and are therefore closer to the axis of rotation; and (iii) use of little fingers, wrist etc. to support or steady the hand in placing sutures.

5.1.2.2 *A corotid endarterectomy*

The author observed a single endarterectomy procedure during March 2002. The operation involved removing a blockage from the main artery to the brain, situated in the neck of the patient, via a longitudinal arteriotomy. The diseased area was identified by a yellowish-blue tinge. The vessel was clamped to either side of the diseased area before being opened and then cleared by hand and by irrigation. Afterwards, a shunt (bypass tube) was placed into the artery before unclamping. The use of the shunt was significant for several reasons:

- The initial part of the procedure, whilst blood flow was prevented, had to be carried out very quickly and efficiently, taking perhaps no more than a few minutes. The consultant in charge undertook this.
- The shunt was placed into the artery to maintain blood flow to the brain during the rest of the procedure, principally the suturing of the vessel.

- To avoid causing a restriction of the vessel, a Dacron (synthetic) patch was cut to shape over the wound and sutured in place, working around the bypass tube.
- Because working was hampered by the shunt, and the position of the wound within the joint of the neck, 'perfect' approach angles of 90° were not available. This part of the procedure took over an hour to complete and was conducted by the consultant and assisting registrar.
- Closure of the wound, using a sub-cuticular (sub-surface) technique took approximately 5 minutes, and was undertaken by the registrar.

5.1.3 Motion analysis

5.1.3.1 *Objectives*

To examine and define possible 'flight path' criteria for suturing, Holbrey *et al* devised a simple system to track subjects whilst suturing a foam pad [210]. An Ascension *Flock of Birds* magnetic tracking device was employed for tracking and 7 dof for the hand and elbow were recorded (3D position and quaternion information). Angles of interest were converted into wound-based coordinates via a simple setup routine based around the location of a straight-line wound, see Figure 5.4. Time was also recorded, since the *Flock* was sampled at a graphics frame rate (25 Hz), but was not explored further here, since speed does not necessarily reflect good technique. Also, variation between individuals (novices, experts etc. see 2.2.2) would not allow ready comparison unless other techniques, such as say, *dynamic time warping* [309], were introduced.

5.1.3.2 *Preliminary results*

As the distinction between pure rotational movement and *curving* (see 5.1.1) was not appreciated until later, pure rotation (define here as γ; obtained by matrix analysis) was thought to be a prime candidate for standardizing individual movements. Figure 5.5 shows four attempts by different subjects (members of the School of Computing with no suturing experience) to suture a foam pad. Part (a) shows that all subjects can be seen to vary the orientation of the needle-driver during insertion, although small variations of a few degrees might be acceptable (this would be difficult to quantify by human observers). In part (b), one user is attempting to force the

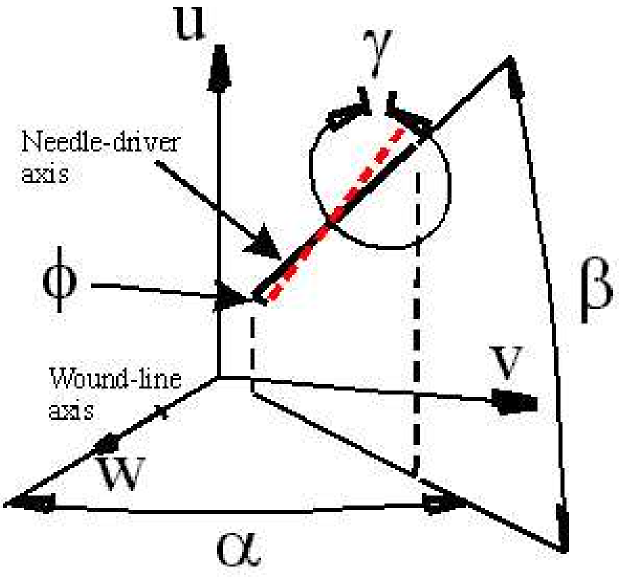

Figure 5.4: Local coordinate/angle system

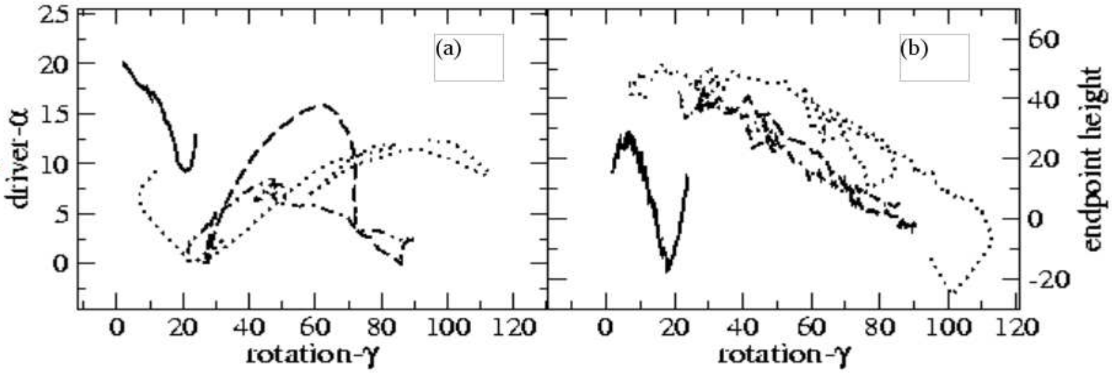

Figure 5.5: Suture technique by angular criteria

needle through by varying the height of the tool, rather than employing full rotation of the wrist, and is very likely causing excessive stress in the tissue.

5.1.3.3 *Discussion*

Whilst these data appeared to give promising results, use of the *Flock* was found to be too restrictive. In particular, the device was thought to be too sensitive to the steel instruments employed during the test so that the sensors had to be worn on the arm or back of the hand. This led to significant errors when the hand was flexed and would probably have made the apparatus unusable for more complex anatomical models. Also, this form of analysis (eg. local coordinate angles, matrix/eigenvector analysis for axis of rotation) was felt to be too complex to give readily understandable feedback to the user, even using graphical techniques such as the 'guide-vector' condition of the BDI study 2.4.3.3.

5.2 Design

5.2.1 Sub-tasks of the procedure

5.2.1.1 *A model operative procedure*

Payandeh *et al* [312] have described the main sub-tasks for suturing as comprising the following actions: position needle, bite tissue, pull through needle, re-position, re-bite, re-pull and pull through. Using the results of the preliminary work carried out in Section 5.1, Payandeh's scheme is developed here to give a breakdown of the main sub-tasks for a typical vascular procedure, see Table 5.1. This is not intended to be all-embracing, but to give sufficient context to plan the setting of the VR environment.

5.2.1.2 *Selection of sub-tasks*

Although suturing is not the only important component of vascular surgeries, a surgeon commonly has to be able to sustain an impeccable level of suturing technique, possibly for several hours at a time. The focus of the current design is, therefore, oriented towards the acquisition and maintenance of a high degree of skill using a suturing needle. Knot-tying has been excluded, not because it is any less important, but because it is very difficult to represent with currently available VR interfaces

	Sub-task	Description	Technique/tools
(a)	Orientate patient	Surgeon takes apt stance or moves patient into position for maximum comfort	Operating table and equipment
(b)	Open wound area	Retraction of skin and subcutaneous fat etc.	Scalpel, retractors, clamps (probably held by assistants)
(c)	Identify diseased area	Tissue probed and examined for discolouration by surgeon in good light	Forceps, magnifier (head-worn)
(d)	Arteriotomy	Vessel opened longitudinally or tranversely	Clamps, scissors, forceps
(e)	Clearing obstructions	Removal of plaques, disease etc.	Forceps, irrigation
(f)	Shunting	Insertion of bypass tube	Clamps, bypass tube
	Suturing:		
(g.1)	Select needle	According to size of bite required, strength and type of needle and suture thread type. Diseased or calcified areas may require a stronger needle	$\frac{3}{8}$ circle needle of various point and thread types, needle holder (various types)
(g.2)	Mount needle	The needle is usually mounted so that the point is forward of 90°	Needle holder, forceps
(g.3)	*Rotation*	The arm is pivoted into position for perpendicular entry into the vessel	
(g.4)	*Pressing* or controlling tissue/needle	Needle driver or forceps used to firm the tissue prior to insertion or removal of the needle. In vascular surgery, forceps may be used to hold the needle, prior reclamping	
(g.5)	Insertion or withdrawal	This action requires the *curving* motion described in Section 5.1.1.	Patch for longitudinal wouds
(g.6)	suture tie or needle re-mounted		
(h)	Closure of wound area	Removal of shunt, clamps etc. and suturing of surface tissues	

Table 5.1: Sub-tasks of vascular procedure

(see 4.3.3.3) and, arguably, has a very good approximation by analogues like the Ethicon® tying board.

A further consideration was that the task should not be so simple or repetitive as to induce a block training effect (see 3.5.8), but should represent a reasonable facsimile without being overpowering. It was especially desirable that the user should be able to set, collect and release the needle at critical points during the procedure. Furthermore, it should be possible to build up skill levels, so that say, for example, the non-dominant hand should also be able to perform the task.

5.2.2 Basic design elements

5.2.2.1 *The operating environment*

Ideally, the surgeon stands at the operating table, looking down at the patient, keeping the arms in at the sides and the elbows flexed at an angle of roughly 90° [142]. The surgeon often has to spend many hours in this position and comfort is therefore important. In order to allow hands, wrists etc. to be steadied in line with sub-task (a) of Table 5.1, it was vital that the scene should be capable of manipulation. Unfortunately, it is not easy to allow haptic devices to be reset, given their limited workspace (see 4.1.3) and, consequently, manipulation of the scene must be led by the graphical application and forces adjusted accordingly.

5.2.2.2 *Use of either or both hands*

Following the findings of earlier research on suturing simulation (see 2.4.3), a principal objective was to incorporate the use of both hands, henceforth denoted as DH (dominant hand) and NDH (non-dominant hand). It should be made clear, however, that for vascular work the NDH does not usually play the same role in restraining tissue as it does for surface wounds. Indeed, it is thought to be bad practice to manipulate vessels directly with forceps, although unavoidable at times. Holding and manipulating the needle or patch with forceps *is* required and at some point it is common for vascular surgeons to have to learn to suture with the NDH.

The attempt to include 2-handed technique immediately suggests several design constraints:

- The deformable model must be capable of representing multiple simultaneous contact points and for vascular models, the choice of contact points must be reasonably large (given the relatively large surface area compared to eg. a liver model);

- The deformable model should be sufficiently accurate so that overlaying deformations, or making large-scale changes with the NDH does not distort the model unduly;
- Collision detection routines must be able to handle multiple contacts at different levels of resolution
  - globally across the mesh at a graphical frame-rate (> 25 Hz),
  - locally at contact with the needle at a haptic frame-rates (1000 Hz);
- The choice of devices for the DH and NDH should permit the angle of the needle to be set and retrieved as naturally as possible.

The asymmetric action of the hands reflects the behaviour described by Guiard [190] (see 3.5.10) and, given the requirement for collision detection (at different levels of resolution), suggested that some degree of parallel processing or threading would be advantageous: the first, with a slower, graphical frame-rate representing the NDH; and the second, with a faster haptic frame-rate, for the DH. The need for realistic deformation and forces suggested that FEM was preferable for soft tissue modelling. Given the complexity of the method, FEM and modifications for the present research are discussed in Chapter 6.

5.2.2.3 *Finite state modelling*

Table 5.2 describes a unique set of needle states associated with the suturing subtasks (g.1-g.6) listed in Table 5.1 with additional states to allow control of collision detection and forces.

5.2.2.4 *Feedback*

The careful segregation of needle states described above (5.2.2.3) allows data to be collected during strictly defined periods of entry, exit etc. Given previous work, and research into training schedules (3.5.8) and augmented feedback (3.5.9), it was thought to be particularly important to allow users to train for an extended period and to be able to obtain feedback when requested. Such feedback should be straightforward to comprehend, but should also aim to exploit the capabilities of the VR environment. In particular, it should aim to:-

Needle state	Description
Rest	Needle returned to rest position to practice grabbing
Grabbed	Needle picked up, ready to set angle for forehand or backhand working etc.
Pre-touch	A region 'in front of' the point of the needle is in contact with the mesh: one (or more) triangles can now be nominated for the local haptic scheme
Touching	The needle is in contact with the mesh but has not pierced it: forces act against the direction of approach
Inserted	Some criterion has been met (see below) to allow the needle to enter: forces now act across the surface towards the point of entry
Pierced	The needle has emerged on the opposite side of the mesh
Relaxing	The needle has been released and hence the mesh/needle should relax to a rest position
Embedded	The needle is at rest in tissue
Regrab-test	The needle is grabbed again, but a test is necessary to establish whether the needle is being inserted further through or being withdrawn
Regrabbed	If the regrab-test shows that the needle has been grabbed nearer the point, the needle is being pulled through and hence it has been regrabbed. Otherwise the needle state should revert to 'Pierced'
Suture	As the needle is pulled through, tension remains on the mesh due to the suture/knot
Override	Added to facilitate jumps between states (see text)

Table 5.2: Finite states

- Be both descriptive (numeric) and prescriptive (ie. to suggest movement corrections).
- Avoid cognitive overload eg. by creating a graphical visualization of errors.
- Avoid dependency formation, by only providing feedback when requested.
- Be motivational: improvements should be easily visible.

At the same time, it was clear that tests performed against the clock would also be required to collect data for assessment of validity and to encourage working under pressure without additional feedback. It was therefore suggested that the design should incorporate modes for testing (with a timed task) and for practice (when feedback can be made available).

5.2.3 Design extensions

Linear finite element models have limited use in general due to their ability to handle only first order strain terms. This corresponds to the initial elastic *Hookean* phase which occurs below the level of 1% strain for most materials. During testing, most tissues exhibit linear behaviour well beyond this limit (see 4.2.2) and it was therefore of interest to see how well, or under what circumstances, stable behaviour for linear FEM continued beyond this limit. It should also be possible to qualify the stability of models by assessing properties such as volume conservation with respect to different elastic coefficients.

If regions of stability could be established, then it might also be possible to generate approximations to non-linear viscoelastic responses in the manner suggested by Raghavan *et al* (see 4.2.2) and explored by Cotin *et al* [113] (see 4.3.4.4).

5.3 Implementation

5.3.1 Approach

The principle of the *asymmetric division of labour* developed by Guiard is used as a central feature of the design here (3.5.10). In his theory, Guiard supposed that the hands might be represented by separate motors, each capable of producing some action independently, but most often acting together (or ‘co-operating’), as if assembled in series. This concept is fully adopted here, although it is necessary to suppose that there are additional mechanisms by which information is fed back from one motor to the other. In essence, *asymmetry* is used to imply that the NDH leads, but makes larger movements at a slower rate, whilst the DH lags, but exhibits finer control and timing is much more critical. The computational load is therefore divided between two processes which support and represent the activities of the hands as follows:

NDH	represented by a slow cycle of movement (ie. a computational loop which operates at a graphics frame rate of *c*.30 Hz), in which changes to the mesh by the NDH drive updates to collision detection and graphical state of the entire mesh;
DH	a much faster computational cycle which generates deformation and force computations by considering contacts with one or more contact triangles, which may be determined by the NDH.

Ideally, we might wish that these processes could operate autonomously. In practice, however, it is necessary to consider a third motor, since the PHANToM haptic device creates its own process and requires strict updates at 1000 Hz. In the kinematic chain of Figure 5.6, therefore, the haptic driver is set to rotate at 1000 Hz, whilst the graphics loop has to cycle at 30 Hz. Intriguingly, this scheme would seem to allow the FEM deformation computations to be carried out at any speed between these limits. In practice, it was seen that interpolation between FEM force computations is very noticeable below 200 Hz.

Unlike a simple kinematic chain, Figure 5.6 shows that the computational process requires a sophisticated communication process to maintain synchronisation:

- The haptic 'motor' supplies a current matrix transformation, according to the position of the endpoint of the PHANToM; during this update (which requires a *mutex* in thread terminology), forces computed from the previous matrix position are returned to the haptic system for rendering.

- The current matrix is used by the DH 'motor' to compute interactions and resultant forces by the needle with the current collision detection mesh; deformations are passed to the NDH 'motor' in return for any updates to the current contact triangle;

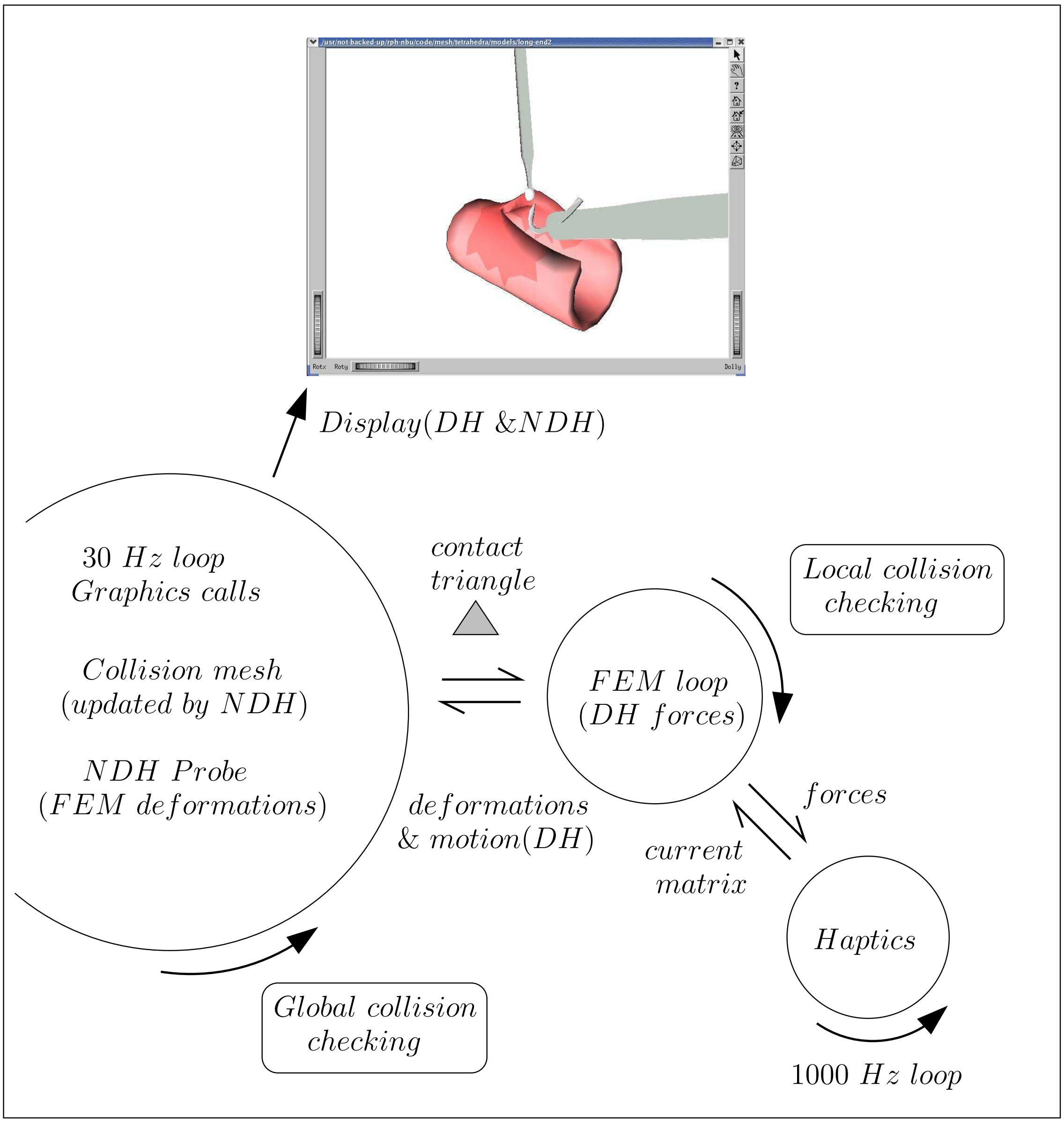

Figure 5.6: Kinematic chain approach

- The ‘NDH’ motor polls for activity by the NDH for updates to the mesh and for any changes requested by other devices (keyboard, mouse etc and so on); updates to the mesh are then passed to the graphical display.

Further details regarding the implementation of this ‘motor-chain’ approach are given in Section 5.3.7.

5.3.2 Platform

A Dell 3.06 GHz dual-processor PC with 2GB RAM and nVidia FX2000 graphics card was used. CrystalEyes stereo glasses are used to provide a sense of depth for targeting the ‘needle’. Force-feedback is provided by SensAble Desktop Phantom (6dof input, 3dof display). A pair of ratcheted (locking) needle holders has been attached to the latter, in such a way that opening and closing of the grip lock is still allowed, see Figure 5.7.

Figure 5.7: Hardware

To investigate the stability of forces and to provide additional facilities to interact with the scene, a Spacemouse Plus device (Figure 5.8 [28]) was employed in the NDH to manipulate ‘tissue’. In future, this may be replaced by a more appropriate device: it should be noted, however, that the main objective is to train the dominant hand by varying the access conditions, and that, in any case, training should encourage swapping the devices between hands.

Figure 5.8: 3DConnection Spacemouse

(from [28])

The operating platform was Redhat 9 Linux with 2.4.26 SMP kernel. The force-feedback device was enabled by Ghost v4 drivers from SensAble [373] and the Spacemouse driver was supplied by 3dConnexion [28]. Open Inventor [376] was used to provide the graphical display and appropriate widgets to rotate the scene to any viewpoint. It should be noted that the open source version of Inventor (v2.15-10) is not 'thread safe', but can be used if graphics calls are maintained on the same thread. The FEM code was adapted from Chandrupatla and Belegundu [94] to interface with solvers from LAPACK [37]. The needle driver and probe were modelled using AutoCAD R.12 [6] and *Art of Illusion* v1.7 [262].

Two forms of attachment for the needle driver were tried: (i) taping the lower arm to the PHANToM handle, allowing the upper arm (operated by the thumb to open the switch (Figure 5.9); and (ii) using a small aluminium yoke attached through the box joint of the tool, the driver was attached to the midpoint of the PHANToM handle and held firm by taping/splinting (Figure 5.10). The first form was lighter to handle but was awkward to swap for right or left handed users. The second form placed the driver much closer to the axis of rotation of the PHANToM, but made the device longer and heavier to deploy. Some discussion of problems related to devices is given in Chapter 7.

Detection of opening and closing the needle driver was performed by using a serial (RS-232) connected switch: a reed switch was attached to the upper (movable) arm and a small magnet to the lower arm. Code for the switch was adapted from the 'Serial Programming Guide' of Sweet [405] and the switch was polled at each graphics frame update.

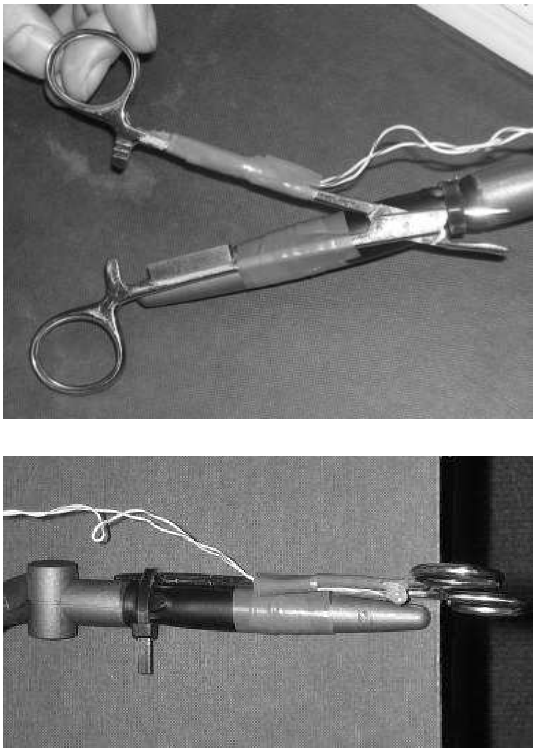

Figure 5.9: Needle driver attachment

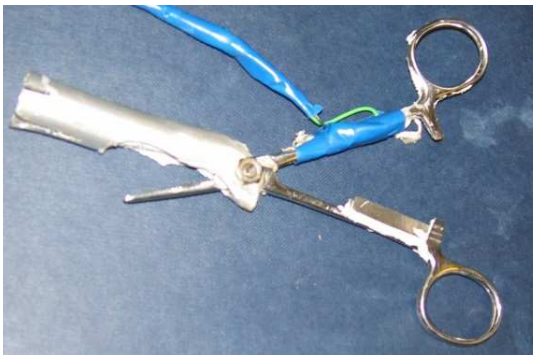

Figure 5.10: Second form of needle driver attachment

5.3.3 Display and posture

For the comfort of the user, an Open Inventor browser display was used, which allows the rotation of the scene using the 'thumbwheel' widgets at the base of the display with the mouse pointer. One of the 'thumbwheels' allows the camera to be dollied ie. moved backwards and forwards to magnify the scene (as if magnifiers were being worn). Stereo display was available through the graphics sub-system and OpenGL related calls in Inventor. Graphics-based calls also allowed the 'grab' and 'tilt' angles of the needle to be set for comfortable working, Figure 5.11.

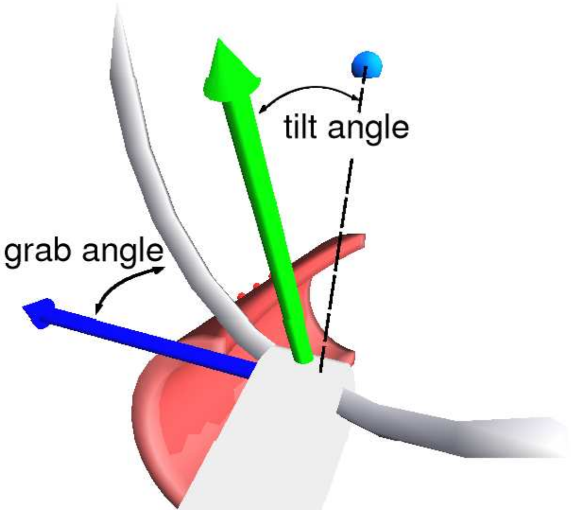

Figure 5.11: Setting the needle angle

Using a combination of these angles, it is possible to set up the needle for at least four positions of working, Figure 5.12. The figure shows that a combination of techniques may be employed on entry and exit, and ideally, all should be practiced. Note that when the needle holder is open, the tool appears as semi-transparent. This is to aid with aligning the tool to the needle. Otherwise, if the jaws are not at tangent, the needle will be rocked into tangential holding position. Also, to aid grasping the needle, a crosshair (not shown) appears when the needle holder is 'in range'. It is convenient here to offer definitions of various error types (refer to Figure 5.13):

- *edge direction error:* the angular difference between the needle normal and the direction of the nearest edge;

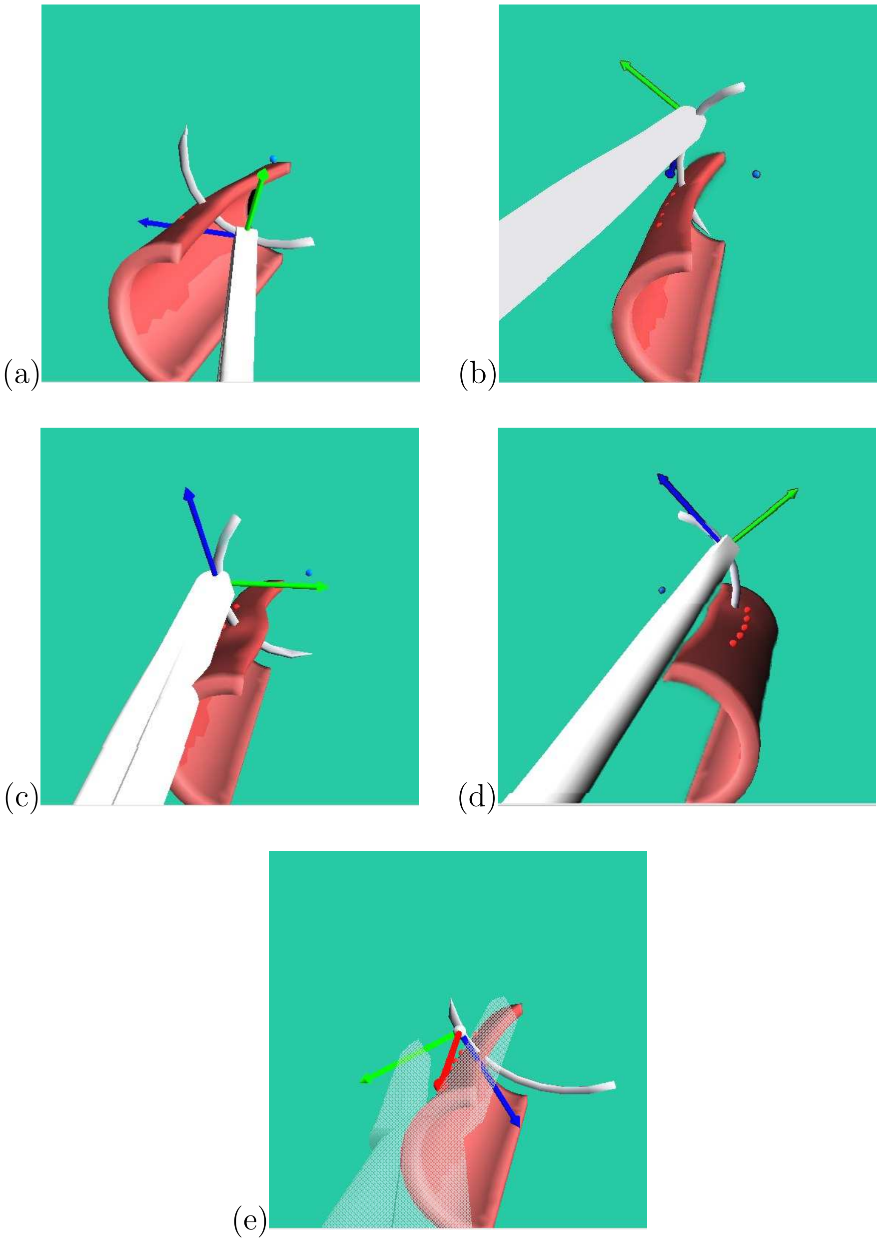

Figure 5.12: Setting working positions

(NB. red/green/blue axes are for this illustration only)

where:
(a) indicates the most common forehand (FH) position ie. FH upright
(b) shows that the needle is tilted downwards, so that the movement is a backhand rotation (FH inverted)
(c) indicates the most straightforward backhand (BH) needle mounting (BH upright)
(d) shows the needle tilted downwards from (c), so that the movement is a forehand rotation (BH inverted)
(e) shows an 'overhand' regrab of the needle (same configuration as (d) — BH inverted). Note that the needle driver is set to be semi-transparent when opened (see text).

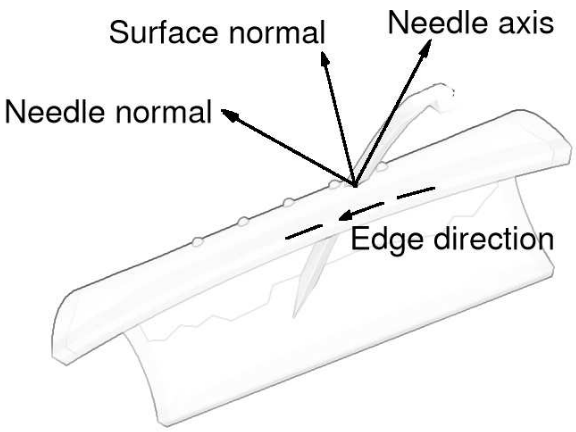

Figure 5.13: Needle approach errors

- *strike angle error:* the angular difference between the surface normal and the needle axis;
- *edge depth:* the perpendicular distance between the insertion point and the nearest edge;
- *centre errors:* the needle centre position should not move ideally — errors can be assessed by finding the average position and deviation from this average during both insertion and retrieval.

Further discussion of error measurements is given in Chapter 7.

The system was deployed from a sitting position at a table for ease of introducing the system. It is recognised that the use of a ReachIn® style mirror [26] gives a more appropriate stance (as for the BDI system, Figure 2.12), but this was not currently available. It should be noted, however, that such a mirror could be added at any time in future.

5.3.4 Finite state model

Unique bits (2^0, 2^1 etc.) were allocated to each needle state of Table 5.2 so that processes executing in parallel at different speeds can be synchronised, using the following simple algorithm. At synchronisation, all threads adopt the value of that with the highest value needle state — unless the 'Override' bit is set, in which case the lowest value is taken.

This is necessary since each process must maintain separate copies of state variables and states do not always advance. Consider the example of grabbing and releasing the needle when the needle is embedded in the tissue model. The reed switch attached to the needle holder is sampled to detect open or closed state at a fairly low (eg. graphical) frame-rate. If the needle holder was found to have closed onto the needle, then the slower thread would then determine that forces should be resumed on the faster (haptic frame-rate) thread. If the needle is still being pushed through from the side of initial entry, the Override bit is set and the system can resume sending forces in the 'Pierced' state. Otherwise, the system can advance to the 'Regrabbed' state and the needle will be allowed to exit legally ie. a stitch has been properly completed.

A suture-thread model was not attempted at this stage and hence 'state' for this level of interaction was not implemented. The main reason for this was that in vascular surgery the sides of the wound are seldom drawn together in the same manner as surface wounds. For example, in longitudinal working, a patch is often used to avoid creating a restriction of the vessel. In end-to-end anastomoses, some 'pursing' of the tissues is inevitable and is one reason for the use of the extra-mucosal technique (see Figure 5.3). This aspect of the present research has therefore been simplified and would be an appropriate area to consider for future work.

5.3.5 Bimanual working

The Spacemouse can be used essentially as a joystick to move a virtual 'probe', which for convenience has a 'hit-and-stick' type functionality. This allows the needle to be used as in the sequence of figures shown in Figure 5.14. An advantage of using the Spacemouse is that it allows the user access to 11 buttons which can be programmed to rotate the needle, activate test mode etc. without requiring the NDH to move from a relatively fixed position. Such facilities can and have been made available through using the keyboard or mouse pointer, but unfortunately, this requires the user's attention to be diverted, making the task considerably more difficult.

5.3.6 Collision detection

A number of collision detection libraries are available in the public domain. Most, however, employ fixed bounding box techniques to optimise detection for rigid bodies. The author is aware of only one exception — the *SOLID* library of van den Bergen [430], which does not yet cope with deformable structures [van den Bergen,

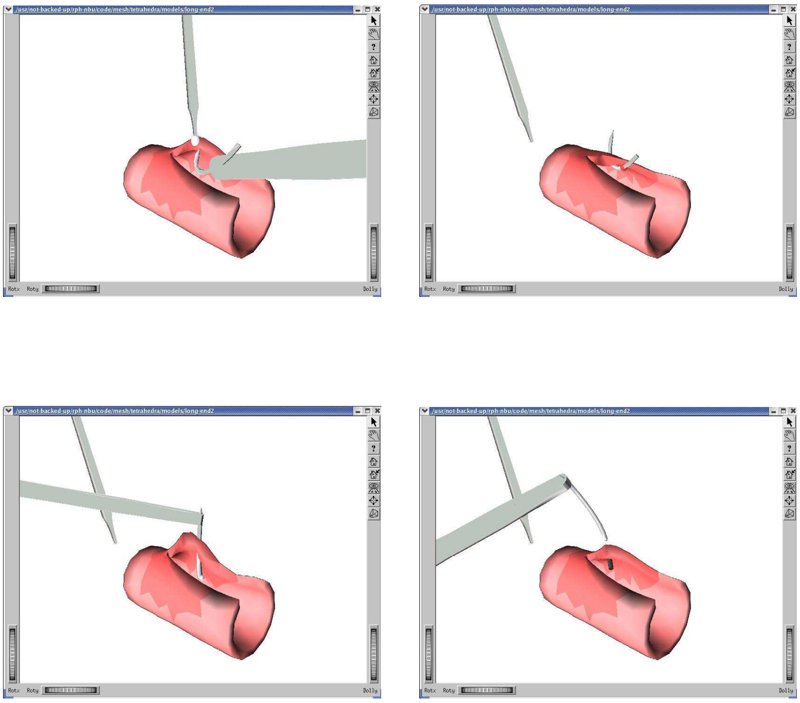

Figure 5.14: Working with both hands

personal communications, June 2002–July 2003]. The hardware based methods of Lombardo *et al* (and others, see 4.6.3) would appear to offer greater scope. The curved shape of the needle, however, did not suggest a simple viewing volume, but rather that a simple ray-based technique might be more appropriate.

The solution adopted here was to separate the basic roles of collision detection into two main components, within the ‘motor’ design of Figure 5.6. Since the ‘needle’ can readily be represented by a collection of line segments, a ray-plane intersection test was devised, comprising three basic stages: (i) ray-plane intersection; (ii) barycentric coordinate computation; and (iii) segment-plane intersection. The collision checking algorithm was adapted according to the position in the kinematic chain and the flow of information is described below. Through trial and error, it was found that stability of the triangle nomination scheme was improved if an additional ray segment (ie. a ‘probing’ segment) was tested in front of the point of the needle, Figure 5.15. The length of the probe was set at twice the distance of previous displacement vector.

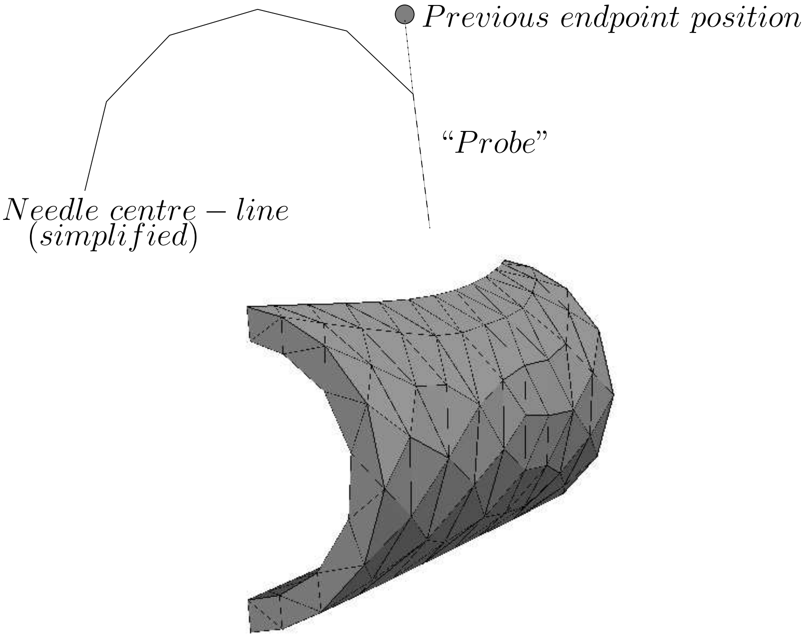

Figure 5.15: Needle probe

5.3.7 Processes of the kinematic chain

5.3.7.1 *Haptic cycle*

The Ghost driver employs threading to provide a real-time schedule, suggesting a mechanism to manage the timing of the threads for parallelisation. In practice, user safety is improved and the interpolation of forces is easier to achieve (ie. extrapolation is unnecessary), if the graphic and haptic displays are delayed by a single video frame (the Phantom must still receive updates at 1000Hz for smooth forces).

5.3.7.2 *FEM cycle*

This thread was permitted to execute at slower speeds than the haptic thread, and the force data interpolated as necessary. The interpolation of forces was found to give poor results if updates were dropped below *c.*250 Hz and 333 Hz was the lowest value used in practice. For most models used in testing and evaluation, however, updates at 1000 Hz were achievable and this rate should be assumed unless otherwise specified.

For the *local* collision detection algorithm, data for the nominated triangle are created and updated during synchronisation with the graphic cycle (see 5.3.7.3). If an intersection is confirmed in the FEM loop, the nomination becomes fixed locally until contact is lost. Barycentric coordinates are used to distribute the impact of the ‘needle’ by weighting each node of the entry face accordingly, the resulting deformations being superimposed. Thus, even if the tool leaves the area of the original triangle, the fidelity of FEM solution can still be maintained.

The angle of entry and a velocity test of the ‘needle’ endpoint are used to determine whether the mesh has been pierced. If so, the segments of the ‘needle’ are tracked through the mesh to determine appropriate releasing and re-grabbing.

5.3.7.3 *Graphic cycle*

The graphic thread is responsible for updating the mesh used in the *global* collision detection algorithm and for passing graphics calls. A set of valid exterior triangles is initially defined (by computing face normals) which is tested at each pass of the graphics loop. If valid planar intersections are found to lie within the test triangle (by checking barycentric coordinates) and the ends of the colliding segment are found to lie to either side of the plane, then the intersected triangle is promoted to the FEM scheme.

Multiple collisions must be checked for plausibility. Since ‘surgical’ errors may still occur through poor technique, the *global* collision checking scheme continues to check the defined mesh set after this point. Manipulation of the mesh by the NDH causes the collision detection mesh (and normals) to be updated.

5.3.7.4 *Display cycle*

The display was considered to form an additional level in the flow of information through the system since the deformation state which arises through interaction of the ‘needle’ (eg. by the DH) is only superimposed graphically (with normals etc. being recalculated for shading). The content of the ‘needle’ interaction buffer was otherwise ignored for collision detection, as, if this were not the case, the delay in timing would cause force discontinuities.

5.3.8 Feedback on performance

Two forms of feedback were proposed and implemented (in *practice* mode):

Real-time A simple real-time condition which was to mark the position of the centre of the needle graphically so that movement could be observed while inserting the needle. The centre was marked by a small blue sphere, see Figure 5.11, and was intended to be minimally obtrusive. The marker can be switched off if the user prefers.

Delayed In practice mode, the normal of entry and exit planes is averaged and can be displayed as a series of individual semi-transparent 'planes' (orange-coloured for entry and greenish-blue for exit). Similarly the average position of the centre marker is given, also for entry and exit, by semi-transparent orange and green marker spheres. The radius of each sphere was set to one standard deviation of the movement away from the centre (strictly: the radius was the square root of the sum of the variances in x, y and z directions). After completing a number of stitches, the user can click the right mouse button to view the scene as in Figure 5.16.

A small cylindrical marker was placed at the position of the entry point to indicate the position of a successful suture. The mode of delayed feedback has a number of advantages which may be briefly outlined as:

- straightforward concepts (unlike stress or rotation axes) which are easy to understand;
- enabling the display of average entry and exit planes, and therefore the average difference;
- the model can be rotated in 3D to examine edge intersection direction eg. Figure 5.16(b);
- centre-markers are easily identified with the concept of the 'blue-dot' position;
- the planes are aligned with entry points, giving an additional cue to spacing. If the centres are not aligned with the planes, this indicates a further source of tissue stress ie. the needle was moved, but kept aligned with its average plane: this is referred to as 'out-of-plane' stress in later chapters.

Yerkes-Dodson (Section 3.5.5.1) showed that learning took place best under pressure, if not excessive: it was supposed that timed trials (3 minutes) were useful to add a modest degree of pressure. During these trials, neither the plane nor centre-marker feedback were available.

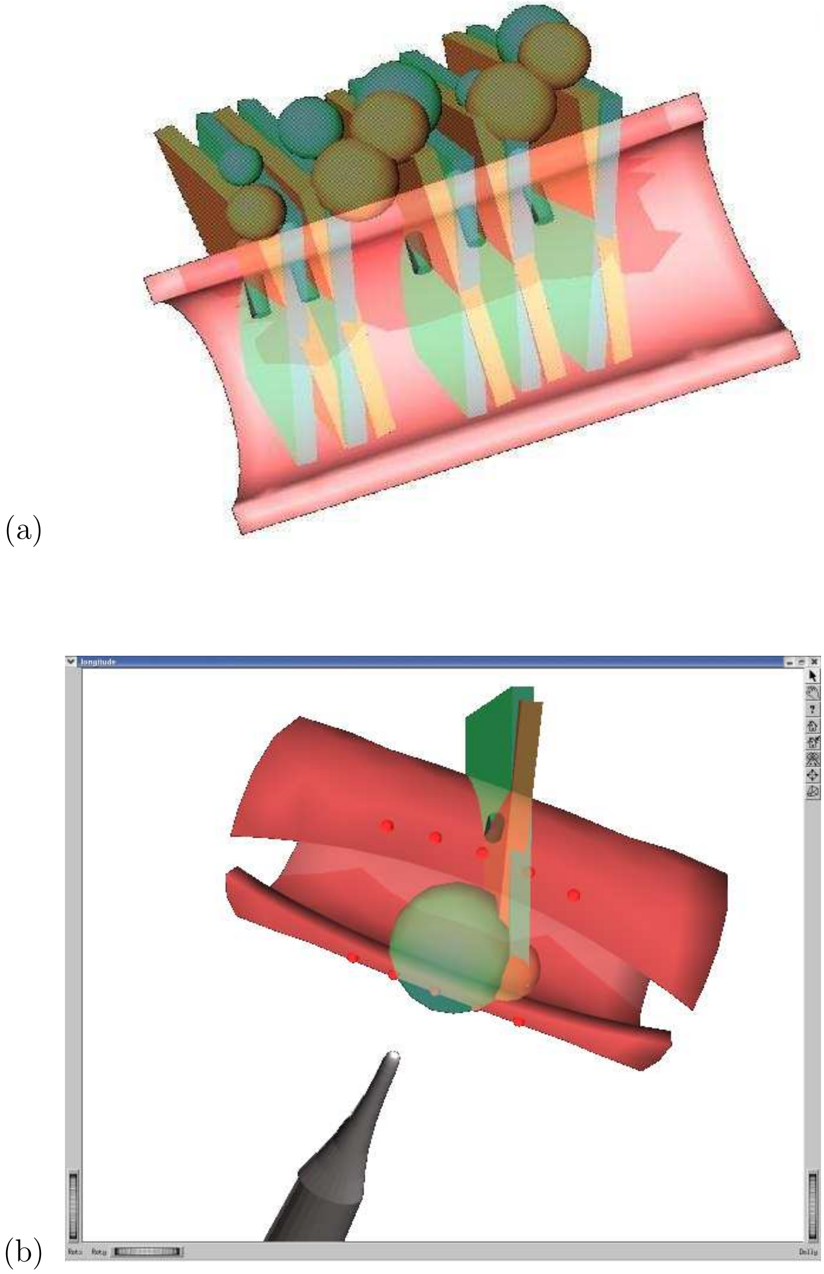

Figure 5.16: (a) Semi-cylindrical model with entry and exit planes; and (b) Longitudinal model and planes from above

5.3.9 Discussion

Several ideas were discussed as possible areas of investigation, for which partial solutions were implemented here but which may merit further analysis in future. One such area was the problem of assessing when the needle has perforated the tissue.

The use of FEM to model the tissue suggested that it may be possible to model this process by using stress analysis. Whilst this would have been ideal in many respects, the difficulty arises that the use of a pre-computation step prevented topological changes and it was not possible to analyse stress levels caused by eg. inserting the needle too near to the edge of the tissue. It is possible, of course, to model perforations in the mesh, but although this was attempted, the collision detection algorithm as outlined did not permit interaction. In any case, a more convincing test, to be undertaken perhaps in future, would be to create a finer mesh and analyse stress levels (off-line) as perforations are placed nearer to the edge of the mesh.

The use of a velocity test to determine insertion, rather than stress, was based upon the suggestion by surgeons that the needle must be used with a certain amount of *conviction*. This would almost certainly depend upon the level of disease within the tissue and is therefore a fairly subjective quantity at present. Again, further work might determine appropriate values for such parameters and the use of FEM would certainly be an advantage in this respect (the choice of parameters set is discussed further in Chapter 7).

One reason that this problem was not pursued further here was that the Desktop PHANToM is unable to return torque forces. It would have been useful, for example, to attempt to model sub-surface layers (or disease) in the tissue in the manner suggested by Frick *et al* (see 4.2.3). This would, however, have required torque forces to indicate resistance to *curving* the needle.

Chapter 6

Solid Mechanics and FEM

This first part of this chapter gives a formal definition of the FEM based upon solid mechanics, elasticity theory and the principle of *virtual work* developed by Huebner [216], Lepi [252] and others. This is a very natural approach but is in fact, a *weak* formulation (see eg. [106] for a stronger mathematical proof). Section 6.3 discusses modifications to allow real-time interaction with vascular models. Section 6.4 examines the stability of these models and proposes an adaption to approximate a two phased linear viscoelastic response.

> ‘At a pinch I could be a tolerable road-sweeper or an inefficient gardener or even a tenth rate farm hand. But by no conceivable amount of effort or training could I become a coal-miner; the work would kill me in a few weeks.’
>
> \- George Orwell, *The Road to Wigan Pier (1937)*

6.1 Linear elastic solids

6.1.1 Stress and Strain

The static deformation problem can be approached by considering the equilibrium between states of stress, expressed as force per unit area, and strain, a ratio of lengths. In one dimension, a bar of uniform cross-section under an axial load can be modelled: in Fig. 6.1, the left end of the bar is restrained (ie. cannot move) but points along the bar are displaced by an amount related to the initial position along the bar, denoted by U. If the portion of the load applied across an infinitely small area, ΔA, is ΔF, we have:

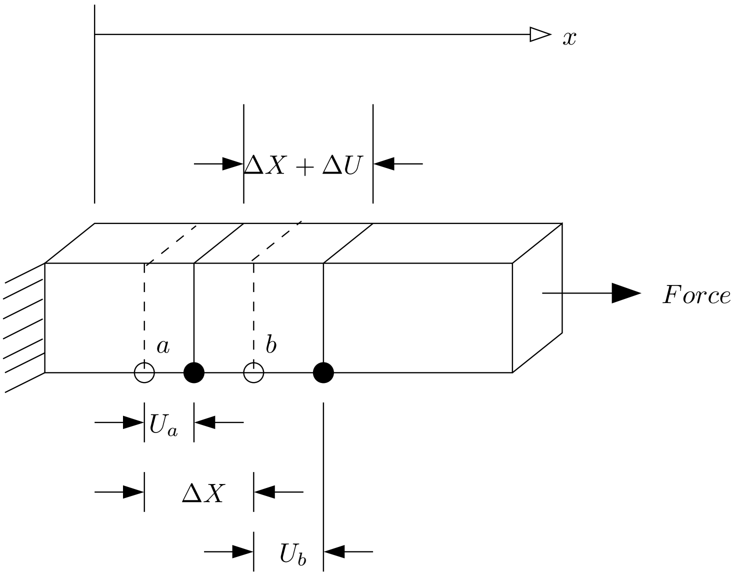

Figure 6.1: Uniaxial strain of a simple bar (after Lepi [252])

normal stress:

$$\sigma_x = \frac{\Delta F}{\Delta A} \tag{6.1}$$

and if the length of the original slice is defined as ΔX and the elongation by ΔU, the normal strain is:

normal strain:

$$\epsilon_x = \frac{\Delta U}{\Delta X} \tag{6.2}$$

In higher dimensions, partial derivatives must be used since displacement is usually a function of more than one variable (and we write $\epsilon_x = \frac{\delta u}{\delta x}$). Unless some other assumption is made (eg. uniform plane stress or strain), interaction in three dimensions will generate nine such derivative components. For isotropic materials, three of these components are dependent (and may therefore be ignored), so that to solve the static problem, six coefficients of the stress tensor must be related to six further coefficients for strain [101]. A 'vector' of normal (σ_i) and shear (τ_{ij}) stress coefficients for any point in the continuum is therefore defined by:

$$\sigma = [\sigma_x, \sigma_y, \sigma_z, \tau_{xy}, \tau_{yz}, \tau_{zx}] \tag{6.3}$$

and similarly, a strain 'vector' for normal (ϵ_i) and shear (γ_{ij}) coefficients:

$$\epsilon = [\epsilon_x, \epsilon_y, \epsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}] \tag{6.4}$$

where the index for normal components indicates the direction with respect to given x, y, z axes. For shear components, the first index indicates the plane within which shear is being considered, and the second index then describes the direction of action. In addition to these vector elements, each strain component can be related to the displacement vector $[u, v, w]$ at a given point by the relations [101]:

$$\begin{aligned}
\epsilon_x &= \frac{\delta u}{\delta x} \\
\epsilon_y &= \frac{\delta v}{\delta y} \\
\epsilon_z &= \frac{\delta w}{\delta z} \\
\gamma_{xy} &= \frac{\delta u}{\delta y} + \frac{\delta v}{\delta x} \\
\gamma_{yz} &= \frac{\delta v}{\delta z} + \frac{\delta w}{\delta y} \\
\gamma_{zx} &= \frac{\delta w}{\delta x} + \frac{\delta u}{\delta z}
\end{aligned} \tag{6.5}$$

if deformations remain small, so that second order terms here can be ignored.

6.1.2 Generalised Hooke's Law

To provide a framework for the development of linear stress-strain relationships, Hooke's Law may be generalised. In one dimension, this is readily envisaged as, say, a uniform rod under the condition of uniaxial normal stress in the x-direction (Figure 6.1). As long as the rod remains within its elastic range, it obeys Hooke's Law as follows:

$$\sigma_x = E\epsilon_x \tag{6.6}$$

E is a material specific constant, called the modulus of elasticity (or Young's modulus). A second parameter, Poisson's ratio, or ν, must also defined to compensate for cross-sectional reduction under uniaxial tension (and *vice versa*), where

$$\epsilon_y = \epsilon_z = -\nu\epsilon_x = -\nu\sigma_x/E \tag{6.7}$$

ν lies in the range 0.25-0.35 for most solid materials, but tends towards the maximum value of 0.5 for incompressible fluids [333].

Applying these relations to 3D (linear) systems in general, we can define the constitutive matrix, $\overline{E}$, which relates the stress and strain vectors (of Equations 6.3 and 6.4) by constant coefficients, so that we can write:

$$\sigma = \overline{E}\epsilon \tag{6.8}$$

where

$$\overline{E} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.5-\nu & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5-\nu & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.5-\nu \end{bmatrix}$$

Furthermore, if we employ the Lamé constants G and λ, given by

$$\begin{aligned} G &= \frac{E}{2(1+\nu)} \\ \lambda &= \frac{E\nu}{(1+\nu)(1-2\nu)} \end{aligned} \tag{6.9}$$

we can write these (six) relationships more succinctly as:

$$\left.\begin{aligned} \sigma_x &= 2G\epsilon_x + \lambda\varepsilon \\ \tau_{xy} &= G\gamma_{xy} \end{aligned}\right\} (x, y, z) \tag{6.10}$$

where $\varepsilon = \epsilon_x + \epsilon_y + \epsilon_z$ and (x, y, z) indicates the cyclic interchange of these indices

[94, 101].

6.2 Finite Element Method

6.2.1 Governing equations

Since we have six equations and at least nine unknown variables in the above, it is necessary to define further governing equations relating to boundary conditions, and in particular, to applied forces. Even in one dimension, however, it is often impossible to give a closed form solution to these differential equations, and numerical techniques must be adopted. Moreover, a static body in equilibrium under 2D/3D states of stress results in a system of second order differential equations given by [94]:

$$\begin{aligned}
\frac{\delta\sigma_x}{\delta x}+\frac{\delta\tau_{yx}}{\delta y}+\frac{\delta\tau_{zx}}{\delta z}+F_x &= 0\\
\frac{\delta\sigma_y}{\delta y}+\frac{\delta\tau_{xy}}{\delta x}+\frac{\delta\tau_{zy}}{\delta z}+F_y &= 0\\
\frac{\delta\sigma_z}{\delta z}+\frac{\delta\tau_{xz}}{\delta x}+\frac{\delta\tau_{yz}}{\delta y}+F_z &= 0
\end{aligned} \tag{6.11}$$

where the terms F_i relate to body forces such as gravitational or centrifugal loading.

The Finite Element Method (FEM) offers the possibility of practical simplification of the geometry and good convergence criteria, providing that [252]:

- the idealisation of the geometric model is reasonable
- the effect of Poisson's ratio is considered: there is no solution to this system, for example, when $\nu = 0.5$ (see Equation 6.10).

6.2.2 Potential energy formulation

FEM may be derived in several different ways. From the stronger, mathematical viewpoint, continuous but piecewise functions of displacement are established across the mesh, which are typically integrated as Galerkin test functions in order to minimise the residual error across the entire region. Since the 'penalty' method is later adapted towards the requirements of haptic simulation, however, it is convenient here to adopt the solid mechanics approach using the concept of the total potential energy (Π), defined as:

$$\Pi = \Pi_\epsilon + \Pi_P \tag{6.12}$$

The Π_ε term defines the elastic or strain energy stored in the body, and Π_P is the work potential of load P. The form of this expression is most easily illustrated by the spring system of Fig. 6.2, where X_1 and X_2 represent two rest states. If the support at X_1 is removed, gravity exerts a force F so that the mass comes to rest at X_2. If $U = X_2 - X_1$, we then have:

$$\Pi = \frac{1}{2}KU^2 - FU \tag{6.13}$$

On the right hand side of this expression, the first term describes the strain energy of a spring with elastic constant K. The second term is negative, reflecting the fact that the potential of the load has been reduced.

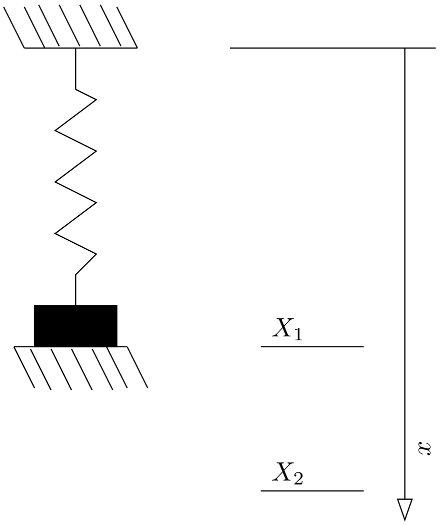

Figure 6.2: Simple spring system

Apart from such straightforward real world analogues, the potential energy formulation is valuable since we may consider a broad class of problems, employing the assumption that:

> *Of all possible displaced configurations that a loaded structure can assume, the displacement that satisfies the essential boundary conditions, and minimises the total potential energy of the system, is the equilibrium displacement [252]*

In the case of the spring in Fig. 6.2, for example, a solution may be readily obtained by supposing that the minimum value of Π occurs where $\frac{d\Pi}{dU} = 0$. In principle, where Π can be defined with sufficient partial derivatives, similar expressions may be readily obtained to solve the displacement problem. The following discussion is intended to provide sufficient background so that the necessary concepts can be covered. More complete proofs can be found in [106, 151, 252].

6.2.3 Energy potential in a thin slice

Fig. 6.3 represents a thin slice of a bar under a uniaxial load[1]. The body behaves as a loaded spring, eg.

$$\Pi_P = -Fu + c_0 \tag{6.14}$$

ie. energy is input as force×displacement (c_0 is the constant of integration). Note that unlike a true spring system, however, u represents a displacement function arising from load being applied at a distance of length L along the bar (ie. u is a function of L). When the load is applied, the right face of the differential slice in Fig. 6.3 is moved by an amount u_2 whilst the left face is displaced by u_1. Examining the work done on the right face, we have[2]:

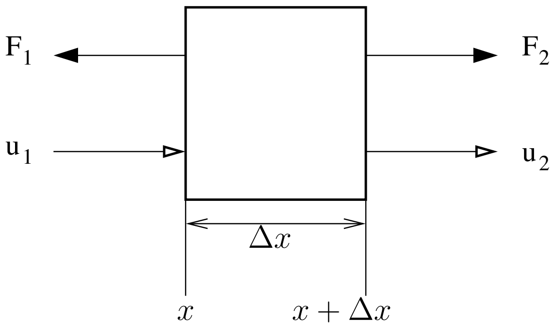

Figure 6.3: Slice of 1D continuum (after Lepi [252])

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[1] We assume here that the left edge of the slice is fixed, and that the force, F_1, is really a reaction. In fact, there is no loss of generality, so long as it is understood that positive displacements, forces etc. are to the right of the figure.

[2] Much of this section summarises Lepi [252] and the reader should consult this text for a fuller explanation.

$$work_{x+\Delta x} \quad = \quad \int_0^{u_2} F_2 du \tag{6.15}$$

and on the left face, since the movement and forces are opposing:

$$work_x = -\int_0^{u_1} F_1 du \tag{6.16}$$

Again, using a spring analogy, the magnitudes of these forces can be written (assuming spring constants c_1 and c_2):

$$F_1 = c_1 u_1 \quad and \quad F_2 = c_2 u_2 \tag{6.17}$$

And so, using Equations 6.15, 6.16, we have:

$$\begin{array}{lcrl} work_{x+\Delta x} & = & \frac{1}{2} & F_2 u_2 \\ work_x & = & -\frac{1}{2} & F_1 u_1 \end{array} \tag{6.18}$$

Assuming that all of the work imparted to the slice is stored as strain energy, Equations 6.18 indicate that the increase in energy associated with the small slice can be expressed as the sum of the two work terms:

$$\Delta\Pi_\epsilon = work_x + work_{x+\Delta x} = \frac{1}{2}[F_2 u_2 - F_1 u_1] \tag{6.19}$$

Since the slice is in static equilibrium, $F_1 = -F_2$, and writing $u_2 = u_1 + \Delta u$ we can obtain an expression for energy per unit length by dividing $\Delta\Pi_\varepsilon$ by the width of a slice, so that we have:

$$\frac{\Delta\Pi_\epsilon}{\Delta x} = \frac{1}{2}\left[\frac{(F_2 - F_1)u_1 + F_2\Delta u}{\Delta x}\right] = \frac{1}{2}\left[\frac{F_2\Delta u}{\Delta x}\right] \tag{6.20}$$

Taking limits for infinitely thin slices, we have:

$$lim_{x\mapsto 0}\frac{\Delta\Pi_\epsilon}{\Delta x} = \frac{d\Pi_\epsilon}{dx} = \frac{1}{2}F\frac{du}{dx} \tag{6.21}$$

or, rearranging:

$$d\Pi_\varepsilon = \frac{1}{2}F\frac{du}{dx}dx \tag{6.22}$$

Since for uniaxial stress, we can define the force as stress×cross-sectional area, A, we have (following Equation 6.6):

$$F = \sigma_x A = EA\frac{du}{dx} \tag{6.23}$$

Combining Equation 6.22 and 6.23, for a bar of length L:

$$\Pi_\varepsilon = \frac{1}{2}\int_0^L EA\left(\frac{du}{dx}\right)^2 dx \tag{6.24}$$

and with expressions for total potential as initially defined (Equations 6.12 and 6.14), it is possible to write:

$$\Pi = \frac{1}{2}\int_0^L EA\left(\frac{du}{dx}\right)^2 dx - (Fu - c_0) \tag{6.25}$$

If we assume that strain energy and potential energy of the load are zero when the displacement is zero, the integrational constants disappear, and the expression for total potential energy for a simple continuous system is reduced to:

$$\Pi = \frac{1}{2}\int_0^L EA\left(\frac{du}{dx}\right)^2 dx - Fu \tag{6.26}$$

In the FEM, it is a natural step to define a single rod-shaped 'element' between nodes at X_a and X_b. Potentials are then calculated for loads applied at both nodes giving the expression (after Lepi [252, Eq. 3.1.1]):

$$\Pi = \frac{1}{2}\int_{X_a}^{X_b} EA\left(\frac{du}{dx}\right)^2 dx - F_a u_a - F_b u_b \tag{6.27}$$

6.2.4 A generic potential energy functional

The strain energy term in Equation 6.24 can be re-written:

$$\begin{aligned}\Pi_\epsilon = \frac{1}{2}\int_0^L EA\left(\frac{du}{dx}\right)^2 dx &= \frac{1}{2}\int_0^L \left(\frac{du}{dx}\right)\left(E\frac{du}{dx}\right) A dx \\ &= \frac{1}{2}\int_V \epsilon_x \sigma_x \, dV \\ &= \frac{1}{2}\int_V (strain)(stress)\, dV\end{aligned}$$

where dV represents the infinitesimal volume Adx. To account for a general state of stress, the stress and strain components introduced in Section 6.1.1 need to be considered. It can be shown that [331]:

$$Strain\,Energy\,Density = \epsilon^T \sigma$$

so that it is straightforward to write (using Equation 6.8) :

$$\begin{aligned} Strain\,Energy,\, \Pi_\epsilon &= \frac{1}{2}\int_V \epsilon^T \sigma \, dV \\ &= \frac{1}{2}\int_V \epsilon^T \overline{E} \epsilon \, dV \end{aligned} \tag{6.28}$$

where, taking $\overline{E}$ as the constitutive matrix defined in section 6.1.2, this expression is then valid across 3D problems in general.

6.2.5 Casting potential into finite element terms

In order to express Equation 6.28 in terms of finite element theory, it is necessary to further decompose the strain vector ϵ into (interpolation) functions based upon element topology. Equations 6.5 give a possible mechanism, but it is necessary to approximate expressions for the displacement variables u, v, w. Moreover, these approximations must contain sufficient partial derivatives ($\frac{\delta u}{\delta x}$ etc) if trivial solutions are to be avoided.

Broadly, the finite element model is created as follows [252]:

1. The object to be modelled is idealised into elements (linear, triangular, tetrahedral, block etc).
2. An appropriate displacement assumption (approximating u, v, w) is selected.
3. The displacement assumption is transformed into an interpolation function.
4. The interpolation functions are substituted into the energy functional.
5. This functional is then integrated to yield a function.
6. The potential energy function is minimised with respect to each nodal displacement variable or *degree of freedom* (dof).
7. Step (6) generally results in a linear system of equations which is usually assembled into a *global stiffness matrix.* Although this matrix is symmetric

positive definite (and therefore offers good convergence criteria), it is also singular until sufficient boundary conditions have also been introduced.

The first step of the process, choosing appropriate elements and defining the mesh, often requires considerable expertise and although caution is generally advised, the requirements of real-time haptic rendering dictate that tetrahedral element and linear displacement assumptions are adopted here. Further discussion of the adequacy of this model is given in Section 6.2.7.

For the present research project tetrahedral meshes were generated using the open source software package Netgen [363], using cylindrical objects as templates. It should be noted, however, that many imaging modalities (such as Magnetic Resonance Imaging) are capable of generating 3D data which can be readily converted into tetrahedral meshes, and the ability to represent living tissues is one of the main reasons why tetrahedral meshes are preferred here.

6.2.6 Interpolation functions

If the uniform bar system of Fig. 6.1 is represented as a 2-node rod element (shown in Fig. 6.4), we can define the deformation function ($\tilde{U}(X)$) along the bar as a linear function of displacement at the end positions. Hence:

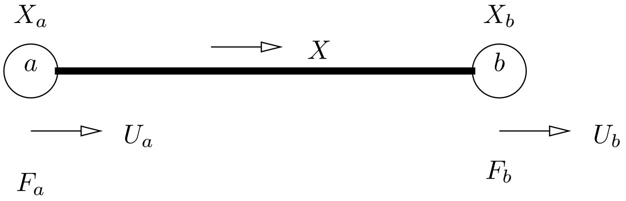

Figure 6.4: Simple rod element (after Lepi [252])

$$\begin{aligned}\tilde{U}(X) &= \left(\frac{X_b - X}{X_b - X_a}\right) U_a + \left(\frac{X - X_a}{X_b - X_a}\right) U_b \\ &= N_1 U_a + N_2 U_b\end{aligned} \tag{6.29}$$

where the displacements U_a and U_b describe the available *degrees of freedom* (dof) along the x-axis, and N_1, N_2 are known as *shape functions.* If we write $X_b - X_a = H$ (a constant, equivalent to the length of the element), it is then possible to approximate normal strain as:

$$\begin{aligned}\epsilon_x &\approx \frac{\delta \tilde{U}}{\delta X} = \frac{\delta}{\delta X}\left(N_1 U_a + N_2 U_b\right) = \left[\begin{array}{cc} \frac{\delta N_1}{\delta X} & \frac{\delta N_2}{\delta X} \end{array}\right] \left\{\begin{array}{c} U_a \\ U_b \end{array}\right\} \\ &= \left[\begin{array}{cc} -\frac{1}{H} & \frac{1}{H} \end{array}\right] \left\{\begin{array}{c} U_a \\ U_b \end{array}\right\} = B \left\{\begin{array}{c} U_a \\ U_b \end{array}\right\}\end{aligned} \tag{6.30}$$

Hence, it is possible to see that the matrix of derived shape functions (B) comprises only constant terms for this element. Given the relation of Equations 6.28 and 6.27, it is straightforward to show that:

$$\left[\int_V B^T E\, B\, dV\right] \left\{\begin{array}{c} U_a \\ U_b \end{array}\right\} = [K^e] \left\{\begin{array}{c} U_a \\ U_b \end{array}\right\} = \left\{\begin{array}{c} F_a \\ F_b \end{array}\right\}$$

and it is possible to see that, given sufficient boundary conditions (say, values of U_a and F_b), a linear system exists which can be used to generate an approximate solution. The term $[K^e]$ is commonly called the *element stiffness matrix.* Furthermore, if $u = [U_1, U_2, U_3, ..., U_n]^T$, this notation can be adapted to higher dimensions, since in general:

$$\epsilon = Bu \tag{6.31}$$

and it is possible to rewrite Equation 6.28 as:

$$\Pi_\epsilon = \frac{1}{2} u^T \; [K^e] \; u \tag{6.32}$$

It is notable that this expression clearly parallels that for the simple spring (Equation 6.13).

6.2.7 The tetrahedral element

To define the appropriate *stiffness matrix* for this element, it is necessary to generate interpolation functions $\tilde{U}$, $\tilde{V}$ and $\tilde{W}$, which, given the nature of Poisson's ratio, must be considered as functions of 3D space ie. (X, Y, Z). Defining the $\tilde{U}$ term as for the rod element, see Fig. 6.5, it is possible to write:

$$\tilde{U}(X, Y, Z) = \alpha_1 + \alpha_2 X + \alpha_3 Y + \alpha_4 Z \tag{6.33}$$

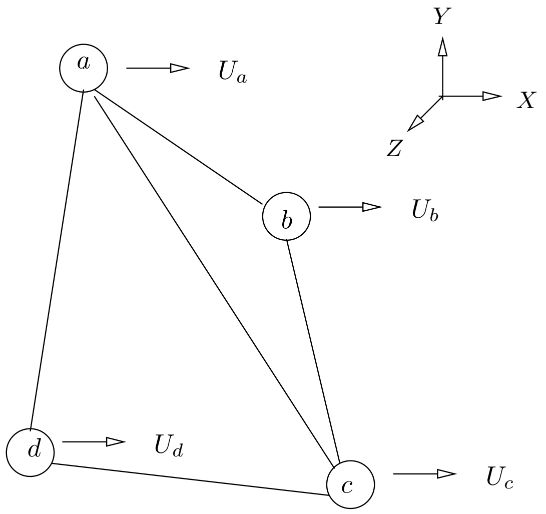

Figure 6.5: Tetrahedral element (after Lepi [252])

where α_i are scalar coefficients. However, it is now necessary to consider functions for displacements at each node of the element, so that:

$$\begin{array}{lllll} \tilde{U}(X_a, Y_a, Z_a) & = & U_a & = & \alpha_1 + \alpha_2 X_a + \alpha_3 Y_a + \alpha_4 Z_a \\ \tilde{U}(X_b, Y_b, Z_b) & = & U_b & = & \alpha_1 + \alpha_2 X_b + \alpha_3 Y_b + \alpha_4 Z_b \\ \tilde{U}(X_c, Y_c, Z_c) & = & U_c & = & \alpha_1 + \alpha_2 X_c + \alpha_3 Y_c + \alpha_4 Z_c \\ \tilde{U}(X_d, Y_d, Z_d) & = & U_d & = & \alpha_1 + \alpha_2 X_d + \alpha_3 Y_d + \alpha_4 Z_d \end{array} \tag{6.34}$$

Writing $U = [U_a, U_b, U_c, U_d]^T$ and $\alpha = [\alpha_1, \alpha_2, \alpha_3, \alpha_4]^T$ and rearranging:

$$U \;=\; \begin{bmatrix} 1 & X_a & Y_a & Z_a \\ 1 & X_b & Y_b & Z_b \\ 1 & X_c & Y_c & Z_c \\ 1 & X_d & Y_d & Z_d \end{bmatrix} \alpha = \left[\overline{A}\right]\ \alpha \tag{6.35}$$

It is straightforward to solve this system by inverting $\overline{A}$ to eliminate the α coefficients using, for example, the symbolic processing functions of Matlab, although the resulting matrix contains over 200 terms and is not given here. Clearly, however, this determination is possible for any valid tetrahedron, and leads to a system purely comprising the elements of U (dof along the x-axis). Hence it is possible to write:

$$\tilde{U}(X, Y, Z) = N_1 U_a + N_2 U_b + N_3 U_c + N_4 U_d \tag{6.36}$$

where, as before, N_i define appropriate *shape functions.* Fortunately this process can be repeated exactly for dof in the Y-axis (ie. $\tilde{V}$) and Z-axis (ie. $\tilde{W}$) with the same resulting shape functions ie.

$$\begin{aligned}\tilde{V}(X,Y,Z) &= N_1V_a + N_2V_b + N_3V_c + N_4V_d \\ \tilde{W}(X,Y,Z) &= N_1W_a + N_2W_b + N_3W_c + N_4W_d \qquad (6.37)\end{aligned}$$

As for the 2D rod-element, these shape functions consist of scalar coefficients (constant for any particular tetrahedron). To compile the B matrix, approximations for the strain terms in Equations 6.5 are obtained by deriving Equations 6.36 and 6.37. It is easy to see that this process yields only scalar terms and thus the 4-node tetrahedron is only capable of representing a state of constant strain. For this reason, many engineers consider the element to be unreliable (eg. [252, 385]). FEM analysts often prefer higher order elements, requiring an additional (numerical) integration step, and although symbolic processing may be able to assist here also, it is not yet possible to consider higher order elements for haptic simulations. At present, this limitation in performance is more easily offset by increasing the number of elements in the original mesh.

6.2.8 The global stiffness matrix, K

Integration of the derived shape functions to satisfy Equation 6.28 results in a 12×12 *element stiffness matrix,* K^e, for each element (related to tetrahedral volume). The rank of K^e reflects the total dof for each tetrahedron, ie. $3n$, where n is the number of nodes. For the whole structure, however, the topology of the mesh surrounding each node must be considered, and (by using appropriate global indexing of dof), contributions from each adjacent element are combined additively. The resulting expression for Π thus includes at least $3n$ terms (one for every dof in the mesh).

Using the minimisation assumption of Section 6.2.2, this expression is greatly simplified. Partial derivatives with respect to each dof yield $3n$ separate *equations*, which may be reassembled into a linear system, usually in the form:

$$K\mathbf{u} = \mathbf{f} \qquad (6.38)$$

where K is the *global stiffness matrix*, $\mathbf{u}$ is the vector of nodal dof (displacements) and $\mathbf{f}$ is the vector of forces applicable at each node. Several algorithms exist to accumulate K (also of order $3n$) efficiently, and care is usually taken at the outset to index nodes so that the number of terms in each equation (the *bandwidth*), is minimised. Since the order of K remains the same, this matrix is usually *sparse* (populated mainly by zeros). Similarly, many techniques exist to reduce storage requirements and ultimately to improve the time required to generate solutions for sparse matrices [106].

6.2.9 Boundary Conditions

Boundary conditions must be supplied since K is initially singular: in effect, the model is free to move by any translation or rotation (suggesting an infinite number of solutions). Three main forms of constraint exist [94, 252]:

- Matrix partitioning: rows/columns are eliminated from the matrix where values of u_i or f_i are known, making necessary adjustments to the remaining elements. This technique disrupts the order of K at each partition, however, and incurs a significant computational overhead through memory operations, even though the number of equations which must be solved is reduced.
- 'Ones on diagonal' method: where u_i is known, this value is inserted in the $\mathbf{u}$ vector and the corresponding row of K is replaced by zeros, except on the diagonal which contains 1. Forces are calculated by replacing the original row, once $\mathbf{u}$ has been evaluated.
- The 'penalty' method: a *large* constant is introduced into K along the diagonal of proscribed dof to simulate the effect of stiff springs being attached at the given nodes. This method is discussed further below (6.3.3).

6.2.10 Solving

Most FEM applications place emphasis upon time required for this phase due to the computational expense, but the solution time is *critical* for satisfactory haptic updates. Of the more straightforward approaches, Gaussian elimination allows processing of multiple 'right hand side' vectors (of Equation 6.38) once the forward step has been completed, but this suggests that the likely contact point (which forms an essential boundary condition) must be previously known. Likewise, conjugate gradient techniques require a significant 'pre-tensioning' step to attain optimum performance.

6.3 Real-time application of FEM

6.3.1 Contribution of this section

In finite element analysis, use of tetrahedral meshes in the arbitrary domain is unavoidable [385], and for haptic displays, the need to generate fast updates restricts our choice to linear elements (ie. models of first order strain). Without pre-processing, and as an initial experiment, it was found that satisfactory haptic performance could be obtained for small models with a single point of contact (<100 nodes, using a 'nearest-neighbour' bandwidth reduction scheme and a banded Cholesky solver).

To allow interaction with both hands, however, a separate solution for each possible contact point is required and pre-processing is unavoidable. The principle of *superposition* [101] can be employed to combine separate displacement solutions, but real-time interaction then requires that each solution be available off-line and loaded into memory, either at programme initialisation, or else as required. This would lead to huge memory requirements, even for fairly modest sizes of mesh and, memory swapping operations might well cause the system to run too slowly. The condensation method of Bro-Nielsen [73] is extended to allow efficient storage and computation of these solutions (and is hence referred to as *super-condensation*).

This section forms a significant contribution towards the present thesis since it describes the theory and implementation of an FEM-driven system which is: (i) capable of representing bimanual interaction (since multiple contact points are allowed); and (ii), capable of outputting to a haptic display with updates at 1000Hz. The result is a rich working environment in which two-handed activities may be encouraged. For convenience, the system is referred to as *Finite Elements (with) Super-condensation (for) Training In VAscuLar Surgery* (FESTIVALS).

6.3.2 Methods of speeding up solutions

6.3.2.1 *Condensation*

The *condensation* technique, first described by Bro-Nielsen and Cotin [73], makes use of matrix partitioning to rearrange the stiffness matrix into blocks of surface(s) and internal(i) nodes:

$$\begin{bmatrix} K_{ss} & K_{si} \\ K_{is} & K_{ii} \end{bmatrix} \begin{bmatrix} \mathbf{u_s} \\ \mathbf{u_i} \end{bmatrix} = \begin{bmatrix} \mathbf{f_s} \\ \mathbf{f_i} \end{bmatrix} \tag{6.39}$$

allowing $\mathbf{u_i}$, the displacement of internal nodes, to be eliminated by inverting K_{ii} and performing a substitution. Condensed systems were initially used to represent large organs or limbs where the proportion of internal to external nodes was relatively high. It might be thought that this approach would have little value for vascular models but medical and pathological phenomena such as atherosclerosis (internal calcification) indicate that meshes comprising several tetrahedral layers could be needed. Nodes which are subject to boundary conditions (eg. parts of the vessel constrained by surrounding organs) can also be eliminated.

6.3.2.2 *Banded matrices*

The matrix partitioning approach was explored further by Berkley *et al* [58], in that partitions were also defined for contact nodes, visible nodes, surface nodes etc. and the matrix organised in such a way that solutions for the most important nodal dof (‘contact’ and ‘visible’) are recovered first. In normal Gaussian elimination, for example, the nodes of greatest interest would be placed at the bottom of the matrix, so that in ‘back-substitution’, equations for these dof would be solved first. The solve process can then be terminated at this point, thus avoiding the need for matrix inversion.

For the current application, however, the need to manipulate vessels during surgery implies that parts of the mesh which were initially invisible (or out of contact) may easily become visible (and contactable) at some point during the procedure. Hence, the banding approach is not considered appropriate here.

6.3.3 Super-condensation

In the original condensation algorithm, the ‘ones on diagonal’ method was favoured for specifying boundary conditions [72]. Using the penalty method, fixed nodes are notionally displaced by stiff springs, which must be included in the energy equation (6.12).

In the penalty method, a stiff spring is introduced to displace the mesh an intended distance, say a_1, but due to the increased strain energy of the body, the vertex is only displaced by an amount u_1, see Fig. 6.6. This increases the total energy by the stored energy of the spring, $\Pi_C = \frac{1}{2}C(u_1 - a_1)^2$, where C is the stiffness constant of the spring. Minimising this expression with respect to u_1, we obtain the additional term: $\frac{\delta \Pi_C}{\delta u_1} = Cu_1 - Ca_1$, which may be included in Equation 6.38, so that K appears as:

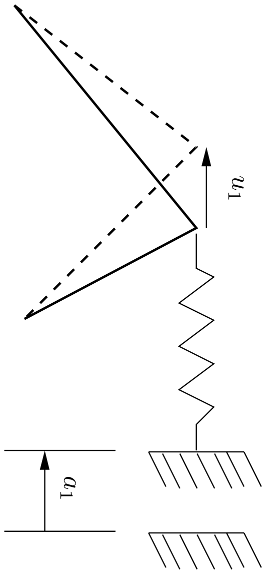

Figure 6.6: Displacements in the Penalty Method (after [94])

$$\begin{bmatrix} k_{00} & k_{01} & \dots & k_{0N-1} \\ k_{10} & k_{11}+C & \dots & k_{1N-1} \\ \vdots & \vdots & \vdots & \vdots \\ k_{N-10} & \cdots & \cdots & k_{N-1N-1} \end{bmatrix} \tag{6.40}$$

and the right-hand side vector now contains displacement terms (appropriate for use with the Phantom [Adams98]) :

$$\begin{aligned} f &= [f_0,\, f_1 + Ca_1,\, \dots,\, f_{N-1}]^T \\ &= [0,\, Ca_1,\, \dots,\, 0]^T \end{aligned} \tag{6.41}$$

The constant C is added along the diagonal of K, where constraints must be imposed. If the nodes are numbered so that entries of K are ordered as contact, fixed and internal dof, then fixed and internal nodes may be removed by the substitution step. The penalty constant is added for each contact node in turn and each matrix is then inverted. Since f now contains only a few non-zero elements (the intended displacements multiplied by C), only the columns of K which correspond to contact dof need to be stored. This results in a *composite matrix*, κ, of inverted K fragments which requires storage for $(3N_{free})^2$ terms. This approach might appear to overlook important *body forces* such as gravity, but it is straightforward to calculate and store an initial deformation solution, which remains valid, so long as the model is not deformed excessively or physically rotated (except about the vertical axis), see below.

The method offers one further gain: the reaction force component is computed as: $R_1 = -C(u_1 - a_1)$. By contrast, the 'ones on diagonal' method requires that rows of the original stiffness matrix must be recalled and each force computation then requires at least $18N_{free}$ operations - a significant additional burden if updates are needed at 1000Hz.

6.3.4 Gravitational effects

By computing a separate stiffness matrix and storing the elements which relate to vertical components, a gravitational effect can also be simulated. This might be used as a variation to make a particular task, say end-to-end anastomosis, more difficult to master, see Figure 6.7.

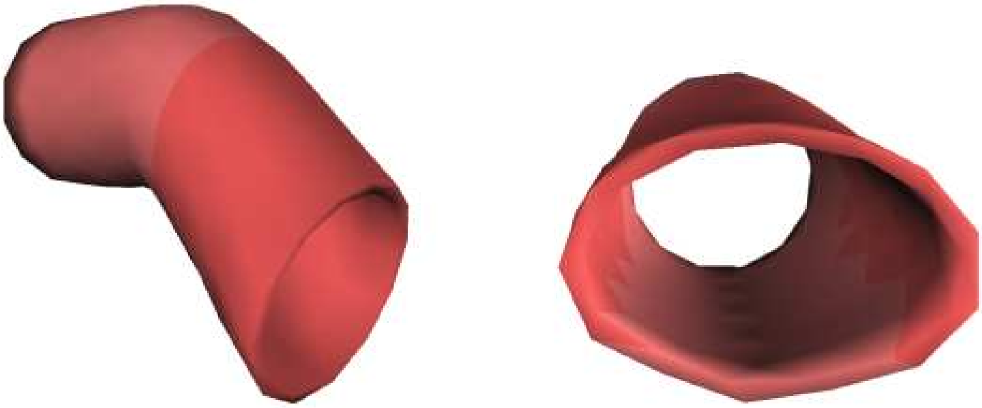

Figure 6.7: Gravitational effects

6.4 Bi-phase model

6.4.1 Contribution of this section

In order to test the stability of the super-condensed model, a range of tissue parameters (for Young's Modulus, E, and Poisson's Ratio, ν) were explored. Through investigating different values for E, it was suggested that using a combination of models may be possible to replicate the 'J'-shaped response curves of eg. Raghavan *et al* (see 4.2.3). This was found to be relatively straightforward, given the work just completed above, but required further analysis to allow a smooth transition between the different elastic models. This section forms the second major contribution of this thesis towards deformable simulation modelling (after 6.3.1).

6.4.2 Testing stability of *FESTIVALS*

In the current simulation, it was found that $E = 100\,kPa$ gave a fairly strong response, and so most useful models were constructed using values at or below this figure. Since matrix inversion increases instability [121], and the penalty method increases stiffness [252], a smaller value of Poisson's Ratio had to be accepted than ideal (see Section 4.2.2). Depending upon the size and modulus of the model, observation showed evident instabilities with $\nu > 0.47$ and hence this was the maximum value adopted here.

In order to generate an appropriate large-scale deformation by the subordinate hand, the input displacement was applied equally to each node of the contact triangle. As a consequence, the linearity of the model was often exceeded before the 10% strain level. In fact, visually, these discontinuities appeared to be caused by realignments of tetrahedra in order to satisfy volume constraints. For the dominant hand, the displacement is distributed over the nodes of the contact triangle, and this mesh realignment was rarely observed. Indeed, linear behaviour often continues uninterrupted beyond the 60% strain level.

6.4.3 Algorithm

The Lagrangian stretch ratio, λ, was approximated by normalising by the length of the model eg. for the 20 mm longitudinal model of Figures 5.12 and 5.16(b), a 3 mm deformation at the needle contact point represents 15% strain, ie. $\epsilon = 0.15$, or $\lambda = 1.15$. The stability of the model (above 1% strain) indicated that it would be possible to combine solutions to approximate the linear response phases of [327]. Composite matrices, κ_1 and κ_2, were computed for the longitudinal model (281 nodes, 689 elements) for values of Young's Modulus set at $E_1 = 50\,kPa$ and $E_2 = 100\,kPa$. Hence:

- Below the arbitrary strain limit, $\epsilon_{critical} = 0.15$, deformations and reaction forces were obtained using κ_1.

- At $\epsilon_{critical}$, magnitude of the input vector$f$ is recorded as $|f_\epsilon|$.
- Above $\epsilon_{critical}$, the input vector was normalised as $\hat{f}$, and solutions were obtained for inputs $|f_\epsilon|.\hat{f}$ to κ_1, and $(|f| - |f_\epsilon|).\hat{f}$ to κ_2.
- The results were then superimposed.

6.4.4 Results

In choosing such a low figure for ν, it was inevitable that the volume of the mesh would become distorted. Figure 6.8 gives observations of volume *increase* errors (%), associated with λ. It should be noted that:

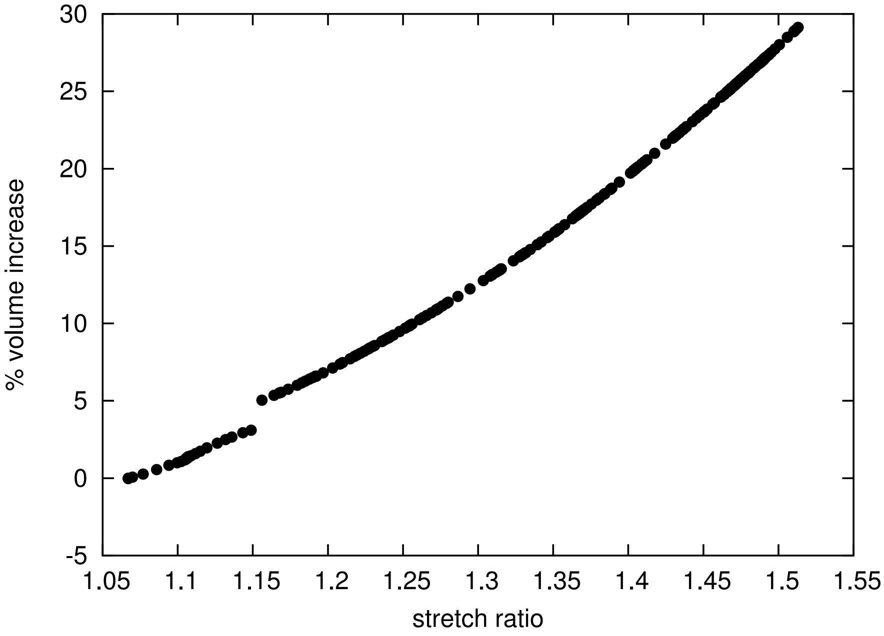

Figure 6.8: Volume error with strain

- using the second composite input causes a discontinuity in the volume change, although this is not generally visible;
- the volume increase error is apparently linear with increasing strain;
- such high strain figures are rarely approached when trying to suture ($\lambda = 1.2 - 1.3$ is a typical limit).

To compare the responses for the tissue-stretching curves of [77, Fig. 3], the stretch ratio, λ (see Sec. 4.2.2) was recorded against the computed reaction force for the 'needle' inserted in the longitudinal model in Figure 6.9. It may be observed that

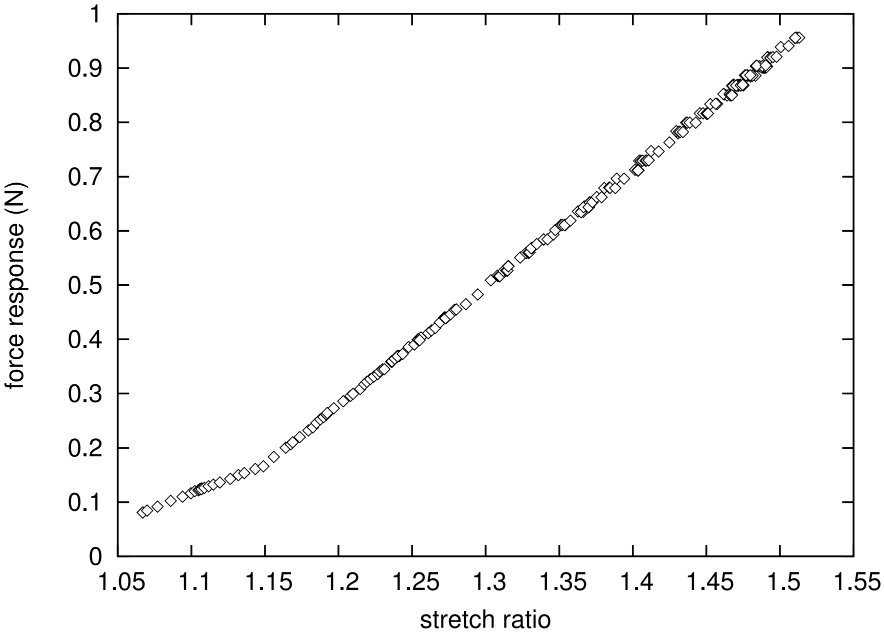

Figure 6.9: Bi-phase linear model

the generated forces appear to be growing more unstable at values of $\lambda > 1.4$ as there is evidence of 'stepping' in the force magnitude curve.

Chapter 7

Evaluation

The chapter describes three attempts to evaluate the *FESTIVALS* system (Section 7.1). The methodology and results of each test are presented in Sections 7.2–7.4. The final section (7.5) discusses the results of these findings as a whole.

‘I wear the chain I forged in life, replied the Ghost. I made it link by link, and yard by yard; I girded it on of my own free will, and of my own free will I wore it. Is its pattern strange to *you*? ’

- Charles Dickens, *A Christmas Carol (1843)*

7.1 Overview

7.1.1 Training premise

In Chapter 2, it was observed that many evaluations were targeted towards improving the assessment of trainees, in order to demonstrate that the tests held *construct validity*. Whilst this property is important, it was argued that testing experts against novices provides only a weak test of the system, and, more importantly, does not give adequate consideration to the issues of transfer and retention. Furthermore, it appeared that many VR simulators added little more than clocking facilities to existing tools, so that the potential for VR to provide a stronger training environment was not being evaluated.

7.1.2 Refining the research hypothesis

In Section 1.4.3, the following research hypothesis was adopted:-

> *Training using a virtual suturing simulator can improve real-world performance.*

For evaluation, the approach taken was to test a set of simpler sub-hypotheses ($H_A - H_C$). These were aimed at basic properties of skill acquisition, namely that:

H_A: performance should display a learning curve with improvement in terms of error reduction, consistency and persistency;

H_B: performance on the simulator should produce improvement using real-world tools;

H_C: performance should not violate the property of *construct validity* as stated: in particular, experts should not find the system more difficult to use than trainees.

7.1.3 Metrics

Whilst efficient movement is of interest, and 'time taken' and 'distance moved' are often the only metrics to show significant differences between experts and novices, it may be that these differences simply affirm the principle of the 'power law of practice'. In other words, repeated practice seems to lead to natural efficiency of movement, whether or not the technique has been mastered. In particular, there may be a trade-off between speed and accuracy (3.5.5.2) and it is therefore vital to monitor errors in addition to time etc. The metrics under test here are therefore based mainly upon the feedback schedule for the *FESTIVALS* system described in Section 5.3.8. In particular, these may be listed as:

- Angular difference between entry and exit planes;
- Strike angle error
- Needle plane to edge direction error;

- Needle centre variation and difference during entry and exit;
- Movement of the needle centre 'out of plane' (principal components analysis);
- Time taken and total displacement during the insertion/retrieval of the needle;
- Total stitch and inter-stitch time.

All participants completed a standard questionnaire for each test, which is described in Section 7.4. Despite the use of specific forms of feedback during development, no form of overall score was generated. This was intended to avoid any possible demotivational aspects of scoring (if, say, scores appear to get worse for a time) and to avoid pressing participants to speed up. Also, it was hoped that using the output from these tests, a more considered scoring procedure could be created.

7.1.4 Statistical evaluation

Several problems relating to the statistical evaluation of simulators have been described, especially in the use of contrasts between expert and novice performances (see 3.6). A further problem arises, however, with attempts to use general linear analysis of variance (ANOVA) models (eg. O'Toole *et al*, Crossan — see 2.4.2.2 and 2.4.3.3 [119, 307]) in that these models do not cope well with non-random effects. In particular, it is important to evaluate the property known as *sphericity* in data.

Repeated measures (or *within subjects*) ANOVA is an attractive and powerful statistical model since the need for control groups is removed and relatively few subjects are required, as differences between subjects are ignored [250]. In fact, the method relies upon three sources of variability: treatment, individual changes and random/residual. An important assumption of this procedure, known as *sphericity*, is that a random factor which causes variation in one subject's measurement to be high (or low) at any point in time should not cause fixed effects in the next reading taken. Failure to correct for violations of *sphericity* can lead to low p-values, and hence Type I error. Many texts advise the use of cross-over designs, and lengthy periods between measurements to allow any fixed effects to be 'washed out' [13]. Several tests for sphericity (eg. using covariance) have been proposed [44, 155, 156, 198], but to the authors' knowledge, where ANOVA tests have been used in simulator evaluation, these tests (or corrections) are absent.

Directed learning is certainly affected by factors such as age, sex and handedness [364]. If other factors could be assumed to be random, or could be as easily screened out, it would be tempting to suppose that the issue of *sphericity* could be ignored. It seems likely, though, that there may be many such confounding factors: fatigue, personal confidence, adaptation to the interface, environmental conditions etc. Corrections for *sphericity* generally involve a process of reducing dof, so that the p-values generated are less significant [44, 198]. Critics point out, however, that this is really an abuse of the random effects model [J. Lindsey, *personal communication*, October 2004] and more specific learning models are usually preferred, such as Markov chains [258]. In game theory, still more sophisticated models have been adopted, such as those related to *equilibria* [87, 403].

Given the early stage of development and limited data sets, more basic t-tests would seem to be preferable. Using t-tests, the problem of sphericity is avoided, albeit with possible loss of statistical power. There is, however, a further problem when comparing the means of many different levels of a factor. Multiple comparisons using t-tests tends to inflate the probability of declaring a significant difference when it is not in fact present[1]. There are numerous *post-hoc* methods to correct for this situation in ANOVA eg. Tukey's Honestly Significant Difference (HSD) method, which is the approach adopted by Crossan (see 2.4.2.2). With these provisos in mind, the reader should be aware that most statistical comparisons will be limited. They are offered mainly for qualitative discussion.

7.2 Test A: Learning curve and retention

7.2.1 Introduction

Previous research has shown that many surgical procedures have steep initial learning curves during which patients would appear to be at considerable risk (Section 3.1). With few notable exceptions, learning curves have rarely been investigated for surgical simulators. Preliminary studies have been undertaken for MIST (Chaudhry *et al* [95], Grantcharov *et al* [187]; see 2.3.2.1) and for the BDI simulator (Murray *et al* [291]; see 2.4.3.3). In Sections 2.5 and 3.6.1, however, it was argued that the failure to appreciate learning curves was a major cause of difficulty with respect to obtaining reliable estimates of validity.

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[1] Because the intervals are calculated with a given coverage probability for each interval but the interpretation of the coverage is usually with respect to the entire family of intervals [323]

7.2.2 Objectives

To study the learning curve of the *FESTIVALS* prototype simulator, this test focuses on the insertion and retrieval phase of each suture since these are most closely associated with the essential *curving* action described in Section 5.1.1.1. The main aims of this test were:

- To chart the improvement, consistency and persistency of a single suturing technique with extended practice;
- To determine possible plateaux or asymptotic levels of performance.

It should be noted that Cuschieri's claim that 'Some surgeons will immediately rise to a level of proficiency…' (2.2.1.1) is specifically being rejected here. Learning curves are complex abstractions which tend to show anything but a straightforward progression — it is 'consistency that counts' [40].

7.2.3 Method

Participants

Due to the time commitment required by repeated practice to build the learning curve, only one subject was recruited. This was a surgically naive subject (age 40, female, right-handed), with no experience of VR.

Task

The task was of a fairly simple format in which the dominant hand was used exclusively with the half-cylinder model of Figure 5.16. Suturing was performed in a forehand (insert) and overhand (regrab) pattern — see Figure 5.12 (a) and (e) — targeting the red beads placed at a depth of 2 mm along the edge of the 'wound'. This action suits the capabilities of the equipment very well (see Discussion), but also provides a more difficult test of skill than the more usual forehand technique.

Schedule

The subject undertook a practice schedule of one-hourly sessions for six days. Practice and 3-minute test trials were interspersed according to the participant's wishes, with four or more trials being completed on each day. In total 43 successful trials were completed; data from 5 tests had to be abandoned due to sensitivities or technical problems with the equipment. The needle holder was attached by ties/tape to the PHANToM as in Figure 5.9.

A retention test of four trials was carried out during a further one-hour session undertaken approximately 6 weeks (40 days) later.

Analysis

The data were analysed and plotted using the GNU/Linux statistical packages 'R' (v.2.0.0) [323] and Gnuplot (v.4.0) [450]. SPSS (v.12.0.1) for Windows was used for some statistical analyses [3].

7.2.4 Results

7.2.4.1 *Errors during insertion and retrieval of the needle*

This section presents a number of plots which focus on the insertion and retrieval phase of each completed suture, averaged over each 3-minute trial. Given the difficulties described above (7.1.4), discussion of statistical significance is generally avoided until Section 7.2.5.

1. *Plane angular error*

    - The curved shape of the needle defines a plane, which is defined mathematically by a normal (and a point in the plane). The average normal during the insertion and retrieval phases was used to compute the respective entry and exit planes, as shown in Figure 5.16. The angular difference between these average planes is defined as *plane angular error*.
    - The 'box-and-whisker' plot of Figure 7.1 displays the distribution of this error for trials (3-minute tests) over the training and retention phases. The parameters of these plots have been set so that the central 'hinge' indicates the median and interquartile range of the variable of interest, whilst the outer 'whiskers' indicate the most extreme data points.

    - It can be seen that the initial performance shows a wide range of variation between adjacent trials, although the median value is predominantly above 20°. The median position is also often skewed, indicating a skewed distribution, but the direction of this skew does not seem to follow any

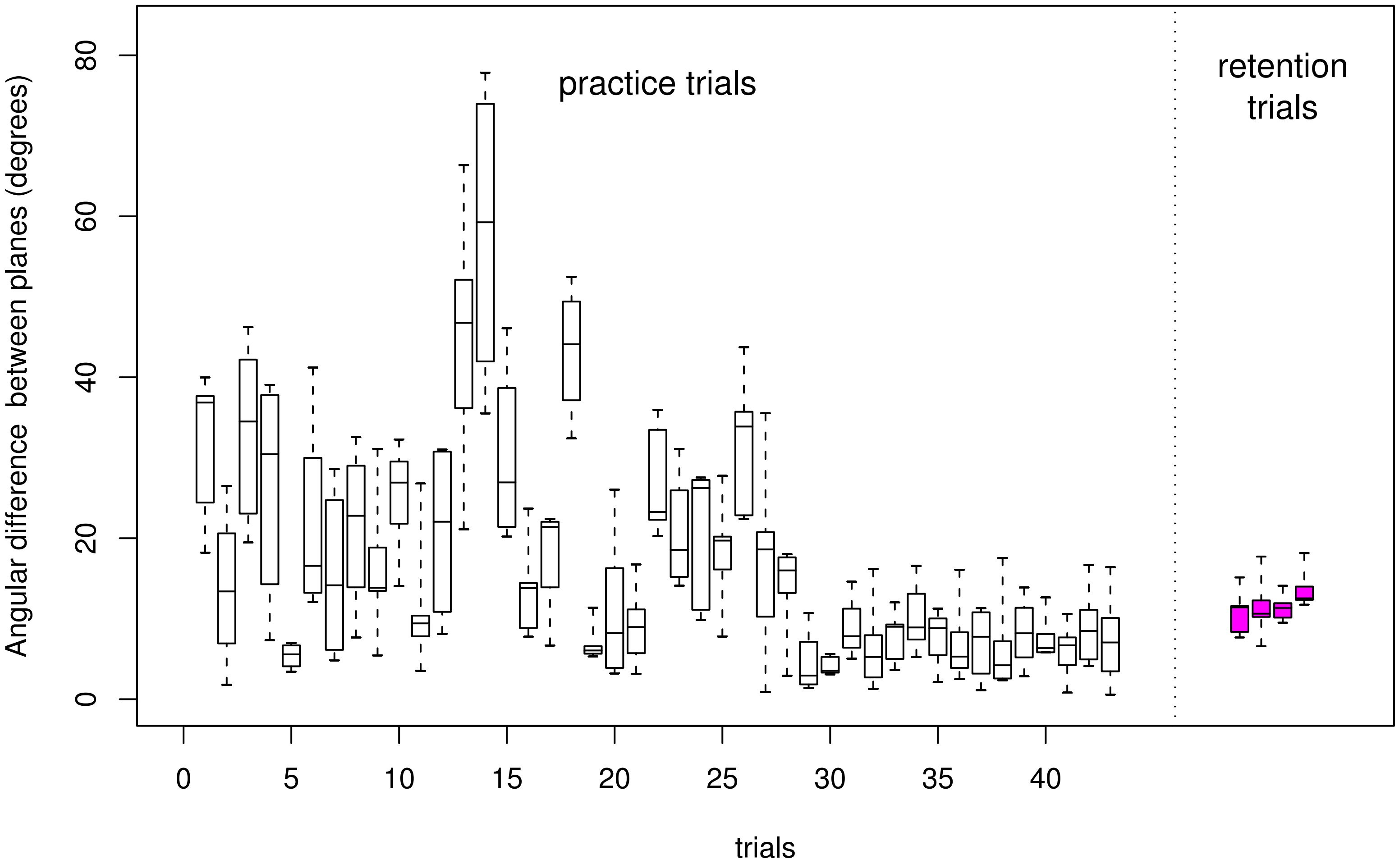


Figure 7.1: Angular error between mean entry and exit planes

obvious pattern. There are also several instances (eg. trial 5) when performance seems to be equal to the final level of performance, but this is not maintained between adjacent trials ie. early performance is generally inconsistent. Intriguingly, this variation in performance seems to get worse (trials 12–26) before consistency improves. After trial 29, the data are markedly more consistent, with a median value generally below 10°. In the retention trials, performance seems slightly depressed by a few degrees, but is still very much reduced — and much more tightly grouped — than initial levels.

2. *Strike angle*

   - The strike angle describes the angle between the tangent of the needle at the contact point and the normal of the surface triangle through which the needle enters. This angle should ideally be close to zero, especially in such a simple model ie. without obstructions from surrounding organs, bypass tubes etc.
   - In Figure 7.2, the data appear to plateau towards a reasonably consistent value of 16–18°. Interestingly, the retrieval data appear to plateau first. Retention performance was comparable with the final level of performance during practice, particularly after the first two retention trials.

3. *Edge direction error*

   - This quantity describes the difference between the average plane normal and the nearest edge direction, as illustrated in Figure 5.13. Figure 7.3 displays an error bar plot for this metric, with mean and ± one standard deviation of the 'stitches' within each trial indicated. Retention performance was comparable with the final level of performance during practice.
   - It can be seen that the pattern of improvement is very similar to that of the plane difference error discussed above, although there are variations between the insertion and retrieval phases. In particular, the overhand regrab action appears to require additional practice before some level of consistency is acquired.

4. *Needle centre movement*

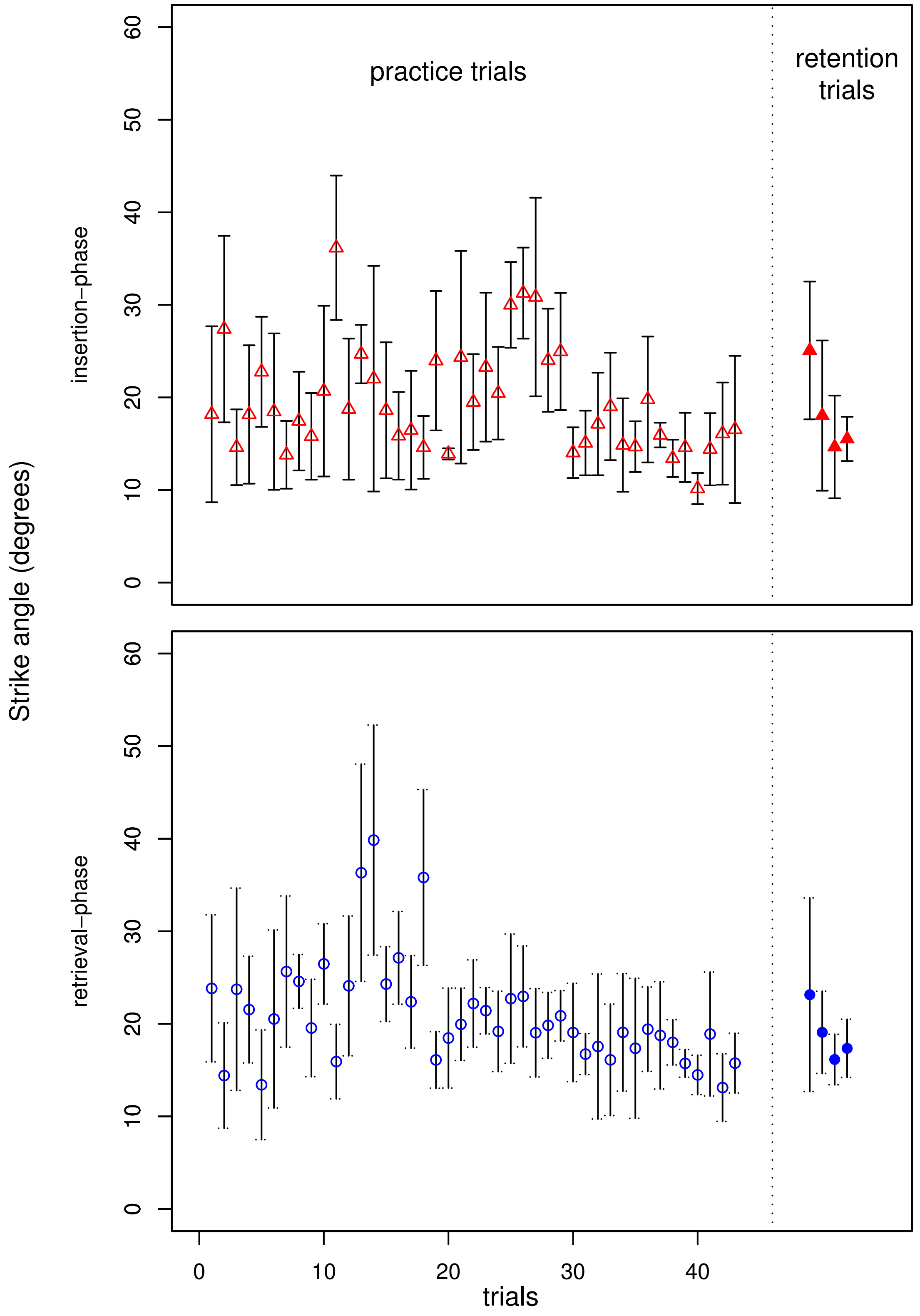


Figure 7.2: Strike angle error

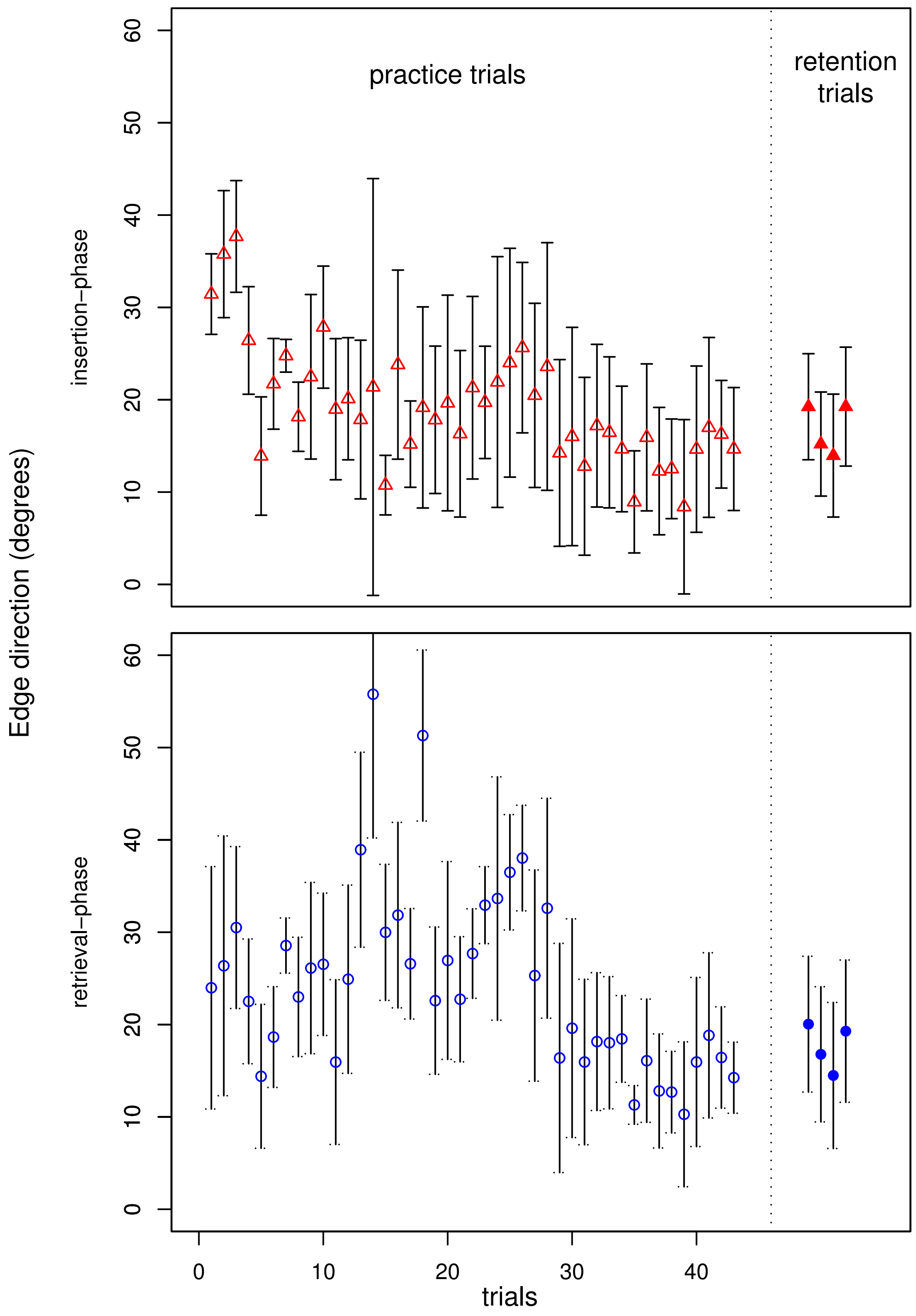


Figure 7.3: Edge direction error

  - This parameter describes the movement about an idealised average centre obtained by post-processing the data for each entry and exit plane. Figure 7.4 shows a small degree of improvement of perhaps 0.5mm over the series of trials although the variance improves only slightly, if at all. There is also some suggestion of increasing consistency in the insertion data, but this is less clear in the retrieval phase. Retention performance was comparable with the final level of performance during practice.

5. *Distance between centres*

    - The distance between centres for insertion and retrieval provide another potential marker. It is supposed that if the averaged centres of movement are close to the ideal *curving* centres, then the two centres (for insertion and retrieval) should coincide. Figure 7.5 provides some evidence of improvement to a consistent level between 1–2mm difference, also maintained in the retention test, and which may be a plateau.

6. *Out-of-plane movement: Principal Components Analysis (PCA)*

    - If the displacement of the needle centre from the average position is computed at each timestep, it is possible to consider an analysis of movement out-of-plane by using principal components. This is useful since monitoring the normal of the needle does not quantify the error due to movement of the needle in the direction of the normal. Moreover, all movement of the needle should be *in* the plane of the needle (ie. at 90° to the normal) whilst *curving* through the tissue. The difference between the first principal component of movement and this preferred plane therefore constitutes a likely error. Figure 7.6 gives a boxplot of this direction error over the period of the trials.
    - From the figure, it can be seen that movement out-of-plane, although evident, is less problematic during the insertion phase: the error reduces from *c*.40° to *c*.25° over the course of the trials. During regrabbing, there was a wide range of errors, often in excess of 50°, although this shows improvement (to *c*.30 °) towards the end of the test.
    - Performance during the retention test was comparable and perhaps even superior to the final level attained practice.

7. *Movement efficiency*

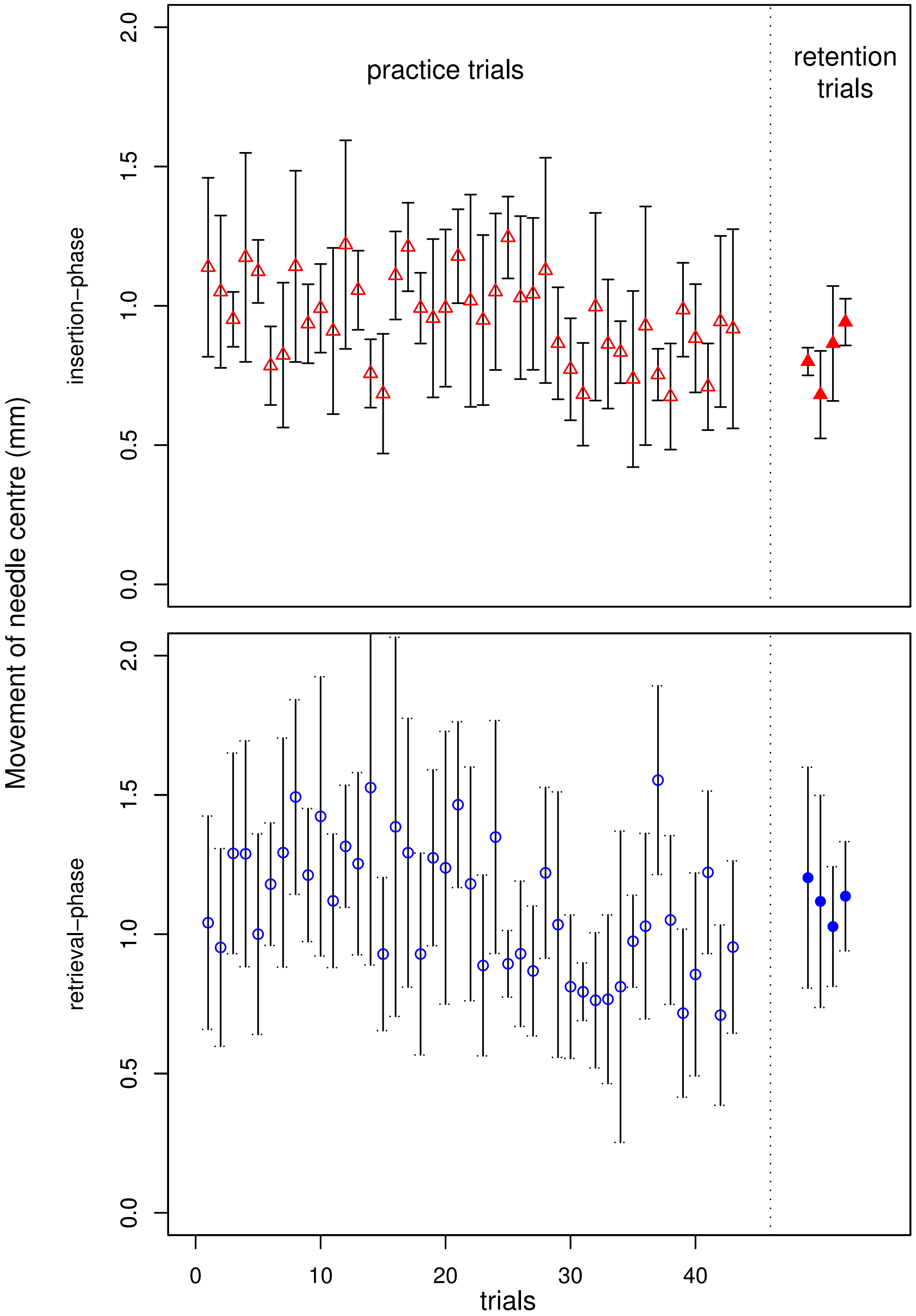


Figure 7.4: Movement of centre

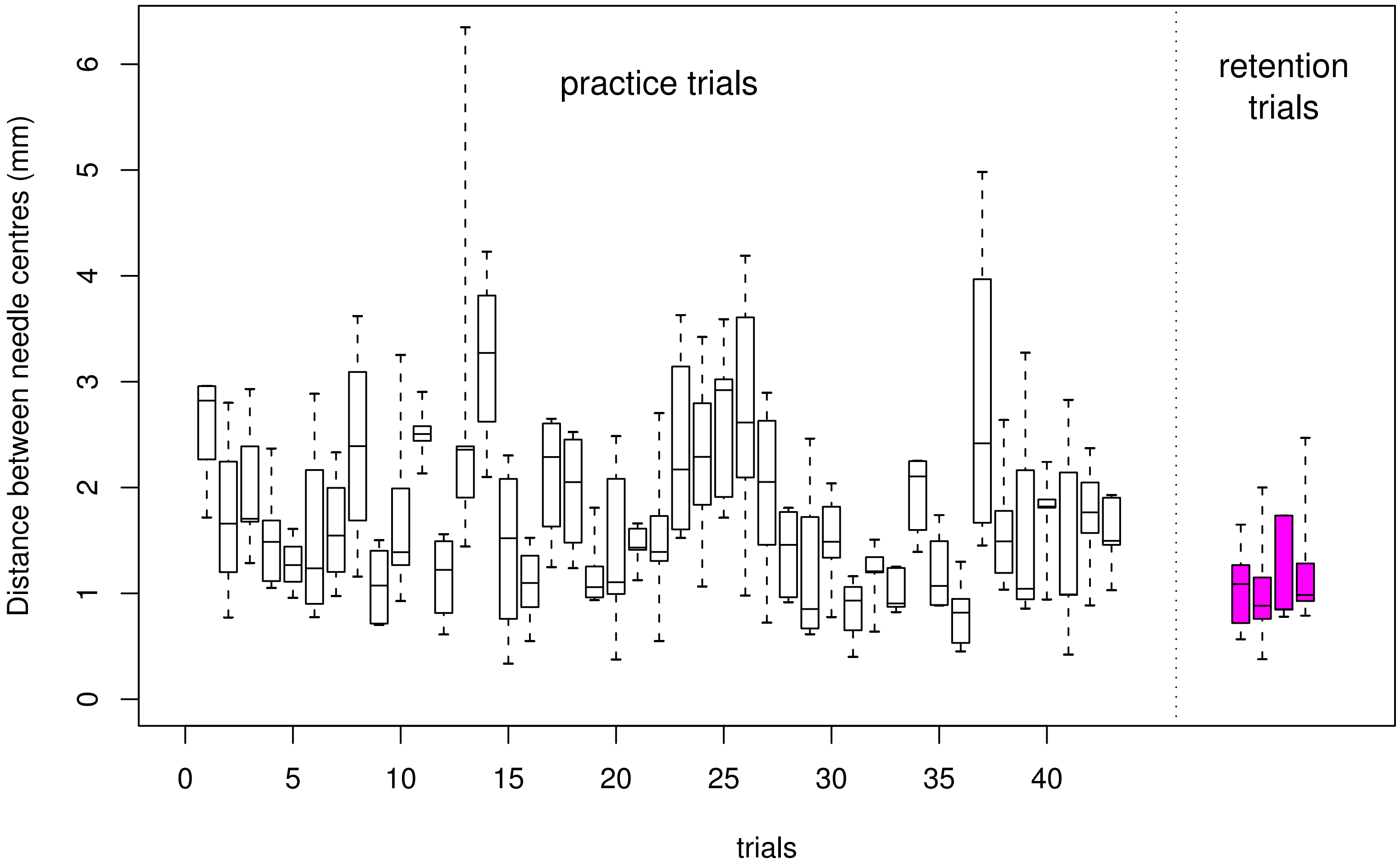


Figure 7.5: Distance between entry and exit centres

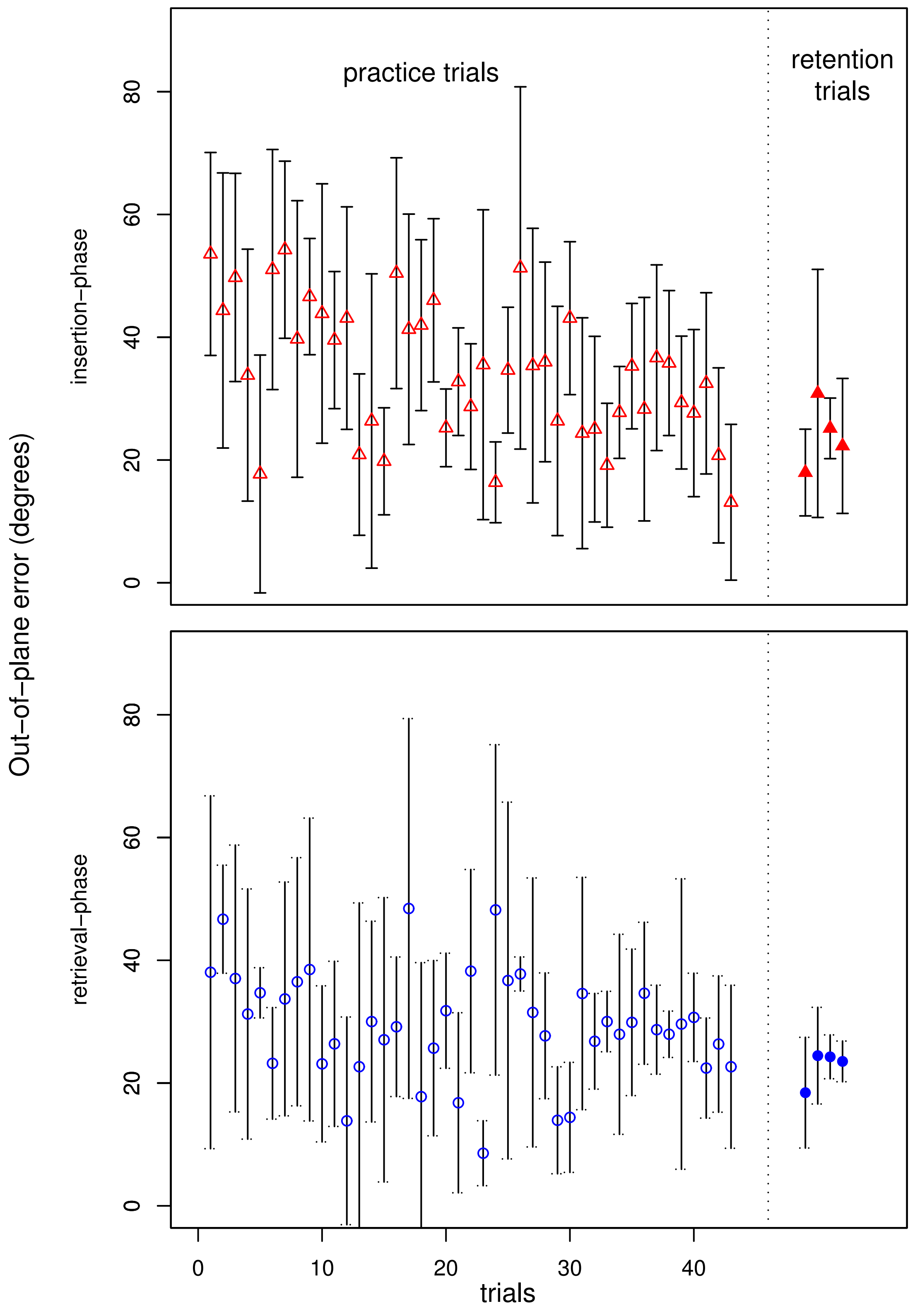


Figure 7.6: Out-of-plane PCA analysis

- Figures 7.7 and 7.8 show the total time and displacement during the insertion and retrieval phases. This data also shows an increasing tendency towards consistency in the later trials, although the trajectories displayed in the figures are divergent, at least in the centre of the chart (trials 12–33). It is particularly interesting to note that this portion of the curve appears to show that retrieval action is being more quickly completed, whilst it is clear from the preceding error plots (Figures 7.3 and 7.4 especially) that this action was the most error prone during period (ie. speed may have been contributing to the error). This suggests that the subject was struggling with different aspects of the task during different stages and speed had to be reduced to make progress in the more difficult phases.

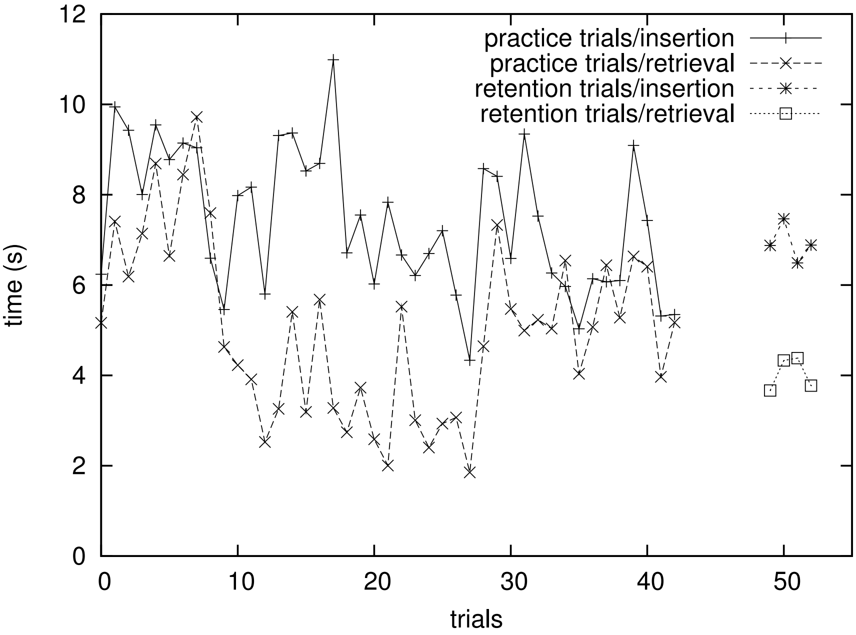


Figure 7.7: Timing of insertion/regrab phases

7.2.4.2 ***Total time and inter-stitch time***

The focus of the present study was not time-orientated ie. the task was chosen to be of sufficient complexity, and feedback was given, such that complete mastery or proficiency was not expected. Since many studies have focused upon this element, however, it seems appropriate to provide some form of comparison here. The study

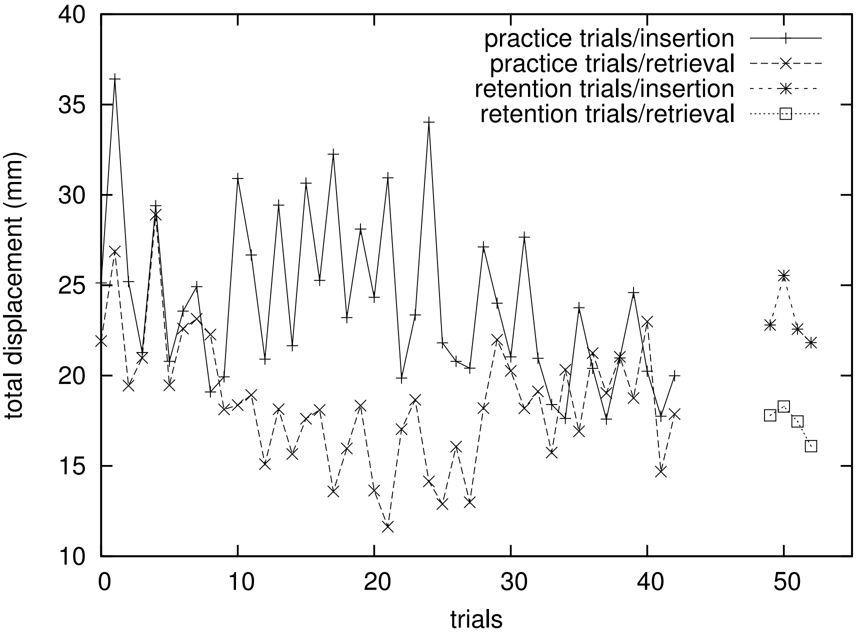


Figure 7.8: Travel during insertion/regrab phases

by Moody *et al* (see 2.4.3.4), in particular, suggested that novices showed exaggerated periods of time between stitches (at rest, setting the needle etc.) which was denoted as the 'inter-stitch' time.

Figure 7.9 present an error bar comparison of the total stitch and inter-stitch time by trial. A small, non-significant degree of improvement is suggested but a strong correlation between the inter-stitch and total stitch time is present (Pearson's $r^2 = 0.680$, $p < 0.001$). It is argued that the data support the view that technical skills were still being acquired and that only a moderate degree of proficiency was achieved.

7.2.5 Performance statistics

Using the empirical observation of 7.2.4(1) that practice trials appear to comprise three phases (I-III), and describing the retention test as phase IV, Table 7.1 shows the significance (p-)values obtained by applying Welch two-sample t-tests over each 'stitch' between phases:

1. I–II (trials 1–11 and 12–28),
2. II–III (trials 12–28 and 29–43),

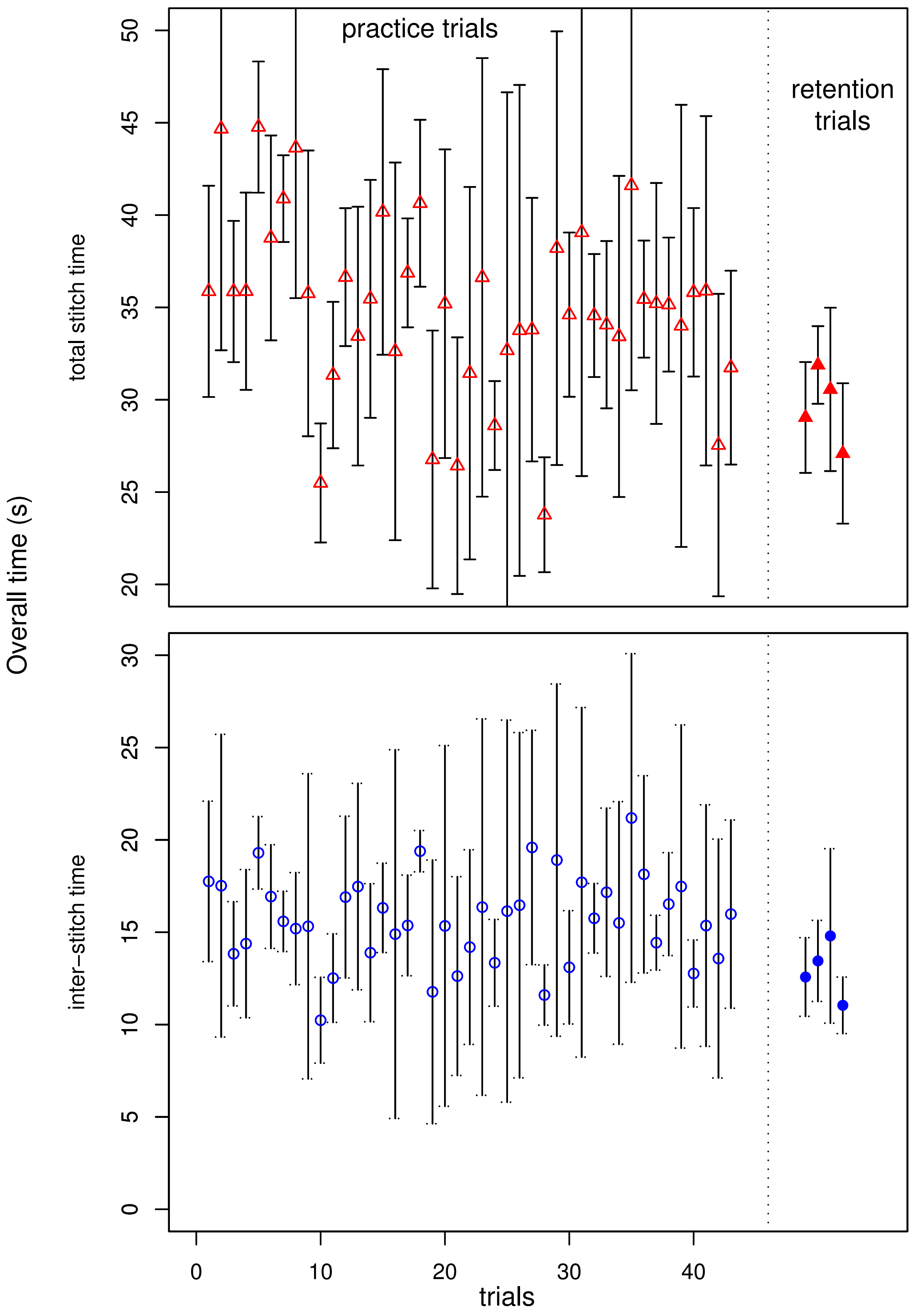


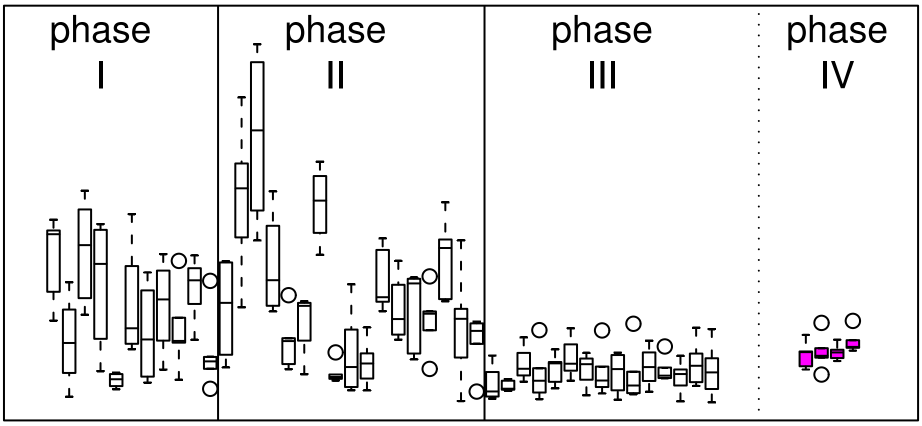
Figure 7.9: Overall time parameters

3. III–IV (trials 29–43 and retention),
4. I–IV (trials 1–11 and retention).

Evidence for the choice of categories used in Table 7.1 was not unequivocal although they were relatively broad to emphasise most distinct changes, ie. with less chance of obtaining significance by accident. All rows contain some evidence of significant changes at least at the $p < 0.05$ level, supporting the view that the chosen metrics were appropriate for study. More surprising, however, is that the table suggests that the largest change occurred between phases II–III, underlining the more consistent nature of the results during the final practice trials (which may be reaching asymptote). The difference between the initial (phase I) and retention trials is similarly marked, with the notable exception of the results for the striking angle. It should be noted that the difference between phases I and III (not shown) was significant at the $p < 0.05$ level, suggesting some loss of performance during the retention tests.

Two further observations may be made: (i) the table shows improvements during many separate phases (even in the retention trials for the out-of-plane error); and (ii) visually at least, Figures 7.1–7.9 appear to show cycles of improvement, which suggests that random effects models are inappropriate (ie. that the data appears to violate the sphericity assumption). In the absence of a clearer learning model, however, it is suggested that the daily schedule of practice, which is roughly comparable to the phases indicated (phase I $\approx$ days 1–2, etc.) may be a source of variation (as was also the case for the microsurgery data 3.1.2).

To examine this effect whilst reducing the potential for false positive significant differences, the plane angular error data were reanalysed using a one-way ANOVA model (without correction) factored by day, with *post-hoc* Tukey HSD analysis. Differences between the 'family' of means (ie. between all the means for each day, with the retention test at 'day 7') are shown in Figure 7.10. The figure displays the confidence interval (to the $p < 0.05$ level) for differences between these means and is significant where zero difference between means is not contained within the interval. Qualitatively at least, the figure shows that central phase of practice (ie. phase II) appears to be distinguished whilst the retention results are comparable to the final level of practice performance.



Test	I–II	II–III	III–IV	I–IV
Plane angular error	0.321	< 0.001	< 0.001	< 0.001
Strike angle				
– *insert*	0.259	< 0.001	0.184	0.322
– *regrab*	0.056	< 0.001	0.305	0.195
Edge direction				
– *insert*	0.001	< 0.001	0.129	< 0.001
– *regrab*	< 0.001	< 0.001	0.338	0.007
Needle centre movement				
– *insert*	0.416	< 0.001	0.720	< 0.001
– *regrab*	0.517	< 0.001	0.020	0.244
Distance between centres	0.520	0.003	0.032	< 0.001
Out-of-plane movement				
– *insert*	0.009	0.021	0.211	< 0.001
– *regrab*	0.268	0.328	0.055	< 0.001
Movement time				
– *insert*	0.126	0.274	0.910	0.011
– *regrab*	< 0.001	< 0.001	< 0.001	< 0.001
– *total*	0.013	0.131	< 0.001	< 0.001
– *inter*	0.725	0.421	0.002	0.037
Movement distance$^+$	0.538	0.004	0.174	0.463

Table 7.1: Significance testing of learning curve

where:

$^+$ indicates aggregated across trials only;

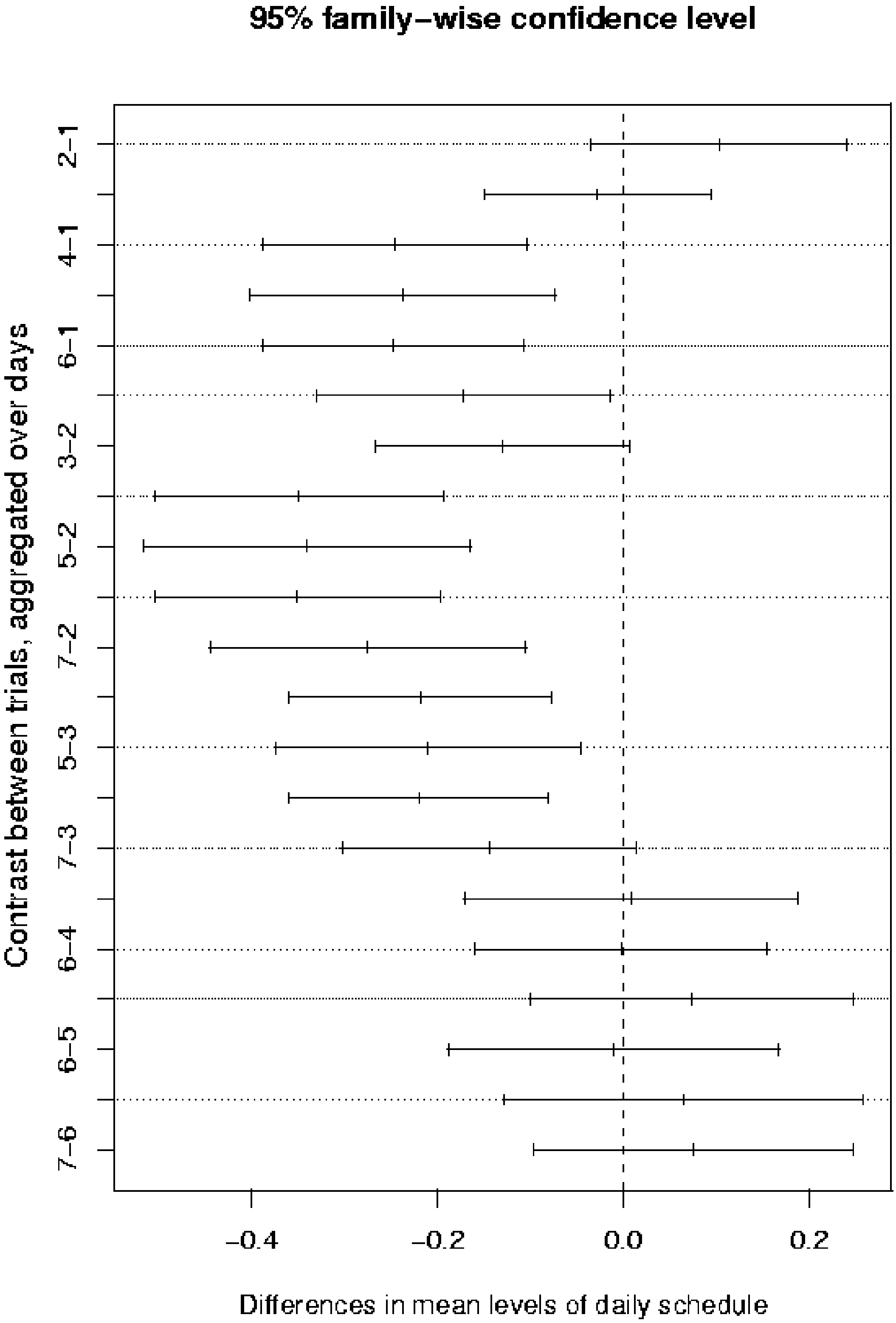


Figure 7.10: Tukey HSD analysis of plane angular error

(Note: The plot shows a family of contrasts between trials, aggregated as per the daily schedule. Significant differences are shown where the 95% confidence range does not cross the axis of expected zero difference.)

7.2.6 Comments

The subject completed a questionnaire, the results of which are included in Table 7.3 below. A number of useful comments were also added, which are condensed below:

- The main improvement seemed to occur early on, after growing more confident for the equipment.
- Even towards the end of the test, it was hard to deal with targeting/overshoot problem even with 3D stereo; it was necessary to keep probing tissue to find the actual working depth.
- The device was physically heavy and made the hand quite sore after an hour's use.
- Rotation of the wrist through such large angles felt rather forced, despite assurances that these were really required.

The interface seems to be the main issue here, and possible influences that this may have had upon the test. Perhaps the most serious is the problem of assessing depth, since it is less easy to see how this difficulty might be improved upon — see Section 7.5 for further discussion.

7.3 Test B: Using real tools

7.3.1 Introduction

This test was intended to provide a direct comparison of the VR simulator with a test using real suturing tools within a synthetic medium. By using a control group, it was hoped that some of the problems of *sphericity*, described in Section 7.1.4, would be bypassed. This study was of limited size, however, given health and safety requirements, which are described below.

7.3.2 Objectives

To identify potential improvements in the use of real surgical tools after a period of training on the *FESTIVALS* prototype. This test is therefore an attempt to assess the *concurrent validity* of the simulator by comparison with an appropriate standard.

7.3.3 Method

Participants

Six surgically naive members of the School of Computing (male, age 35.5±12.6 years (mean±1 sd), two left-handed) volunteered to participate in the test. They were divided into experimental and control groups based upon availability with respect to the task schedule. The voluntary basis of the test had three important restrictive effects: (i) the experimental group contained both left-handed subjects; (ii) the number of training sessions was much more limited than for the learning curve test (Test A); and (iii) the age range of the participants was broader than desirable (youngest 22, oldest 57). All participants had experience of VR devices, but none had any extensive or recent experience of the VR task.

Tools and safety

Tools and synthetic skin-pads were provided by the Suture Tutor Kit (5.1.1.2). For safety purposes a risk assessment was compiled by the author (included in Appendix C), which emphasised the nature of the task and correct holding positions for tweezers, scalpel and needles. It should be noted that due to the use of surgical needles, and limited facilities in the School of Computing for handling *sharps*, it was not desirable to involve greater numbers of participants.

Task

The test task was modelled on the surface wound problem represented by the skin-pad, see Figures 5.2 and 7.11 (and further details in the risk assessment) and was based on the 'mattress' suture technique. One stitch therefore comprises two forehand, and then two backhand suture actions (see Figure 5.12). This requires that the needle is retrieved from the base of the wound at intermediate points. Knot-tying was not practiced, however, and the participants were required to continue suturing, effectively in a 'zig-zag' path. It was supposed that training would improve the quality of the sutures in terms of even spacing, width and symmetry (see Moody *et al*, Section 2.4.3.4).

Pre- and post-tests comprised 10 minutes' suturing, the results being captured by video camera and by scanned/digitised images of the completed pads (eg. Figure 7.12). For the VR training component, the *FESTIVALS* simulator was used with a block type model to mirror the task on the skin-pad, with alternate practice attempts

Figure 7.11: Using the Suture Tutor Kit

(from [20])

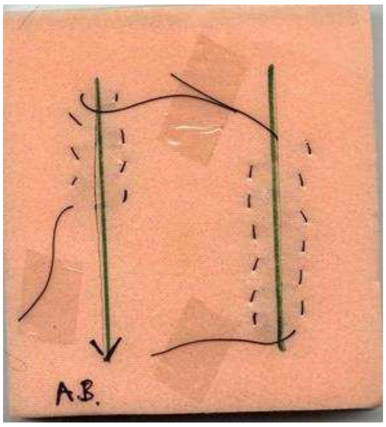


Figure 7.12: Skin-pad, pre- and post-test

at forehand and backhand motions in groups of 5 stitches. Training periods lasted approximately 45 minutes.

Schedule

The schedule was similar to that used to obtain the sample learning curve, so that block training effects were avoided, participants had time to rest and the practice effect of the skin-pad test were minimised. The test schedule is given in Table 7.2.

Day	Control group	Experimental group
1	Skin-pad test	Skin-pad test
2	-	VR practice
3	-	VR practice
4	Skin-pad test	Skin-pad test

Table 7.2: Schedule of the skin-pad test

Analysis

Timing data from the skin-pad tests were obtained manually from video frame counter. Suture path data were digitised from the scanned images of the pads using Corel Draw (v.7) [7] and corrected so that the main axis of the 'wound' was vertical before output with AutoCAD R.12 [6]. The path of the sutures was plotted for each subject, to examine spacing and symmetry.

7.3.4 Results

7.3.4.1 *Synthetic pad data*

The output of the scanned suturing blocks, with the direction of working adjusted to that shown, is given in Figure 7.13. The plot shows considerable variation in the visible suture pattern and it is difficult to identify clear criteria for describing symmetry, especially by a single index. Area to either side of the wound-line, for example, may work well in most situations but would perform poorly if the transformation from the desired 'box' shape was affine (eg. a shear). Also, even if such an index could be found, it would not be expected to reflect the situation within the 'wound'. Two indices were chosen: (i) angular deviations from the path (or transverse) of the wound-line; and (ii) the difference in length between opposite sides of each suture.

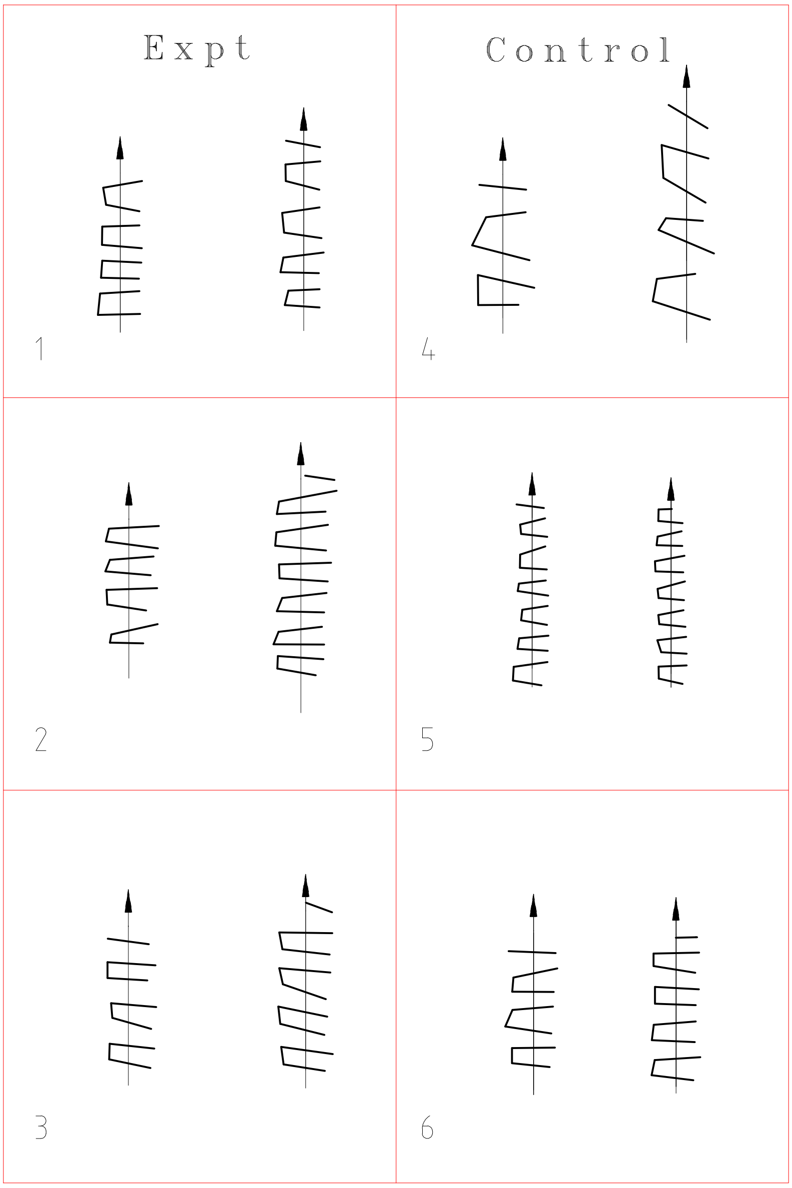


Figure 7.13: Skin-pad suture results by subject

(With pre- and post-test results to the left and right for each individual; the experimental group is to left side of the table, the control group to right side.)

The data for both groups were analysed by linear ANOVA using the data collected from the completed stitches. Analysis of total and inter-stitch time against test (ie. pre-test and post-test) and group (experimental or control) revealed a significant effect for test $p < 0.05$, indicating a strong practice effect for both groups, but a non-significant group or group/test interaction effect. However, if the strongly outlying data from individual '4' (Figure 7.13) are omitted, this leaves a more coherent picture (5 participants, age 31.6±7.7 years, age range 22–39 years) with a non-significant but stronger group effect for time taken per stitch with $p = 0.096$. Similarly, the angular symmetry parameter approaches significance when factored by group, with $p = 0.071$.

Using the variances obtained for total stitch time here, the 'R' package gives an estimate for the statistical power of this test at just over 10%. This implies that even if the simulator was established as an effective training tool, this test would only have given significant results in 1 out of 10 applications. Furthermore, to set the power of the test at 80% (a figure quoted as desirable in many texts), would have required 34 people in both the control and experimental groups. Hence, whilst these results are insignificant by convention, it is suggested that the significance values are of some interest (see 7.5.2).

7.3.4.2 *VR data*

Since the primary objective of this test was to assess performance with real tools, detailed analysis of performance on the simulator is not considered relevant. For comparison with the results above, however, Figure 7.14 presents a graph of mean stitch time data for the experimental group. In general, it can be seen that timing data appear to be improving and converging although for some aspects, performance for two individuals decreased. Performance does not, therefore, appear to have reached a level of consistency (which would not be expected, given the results of the learning curve test, above).

7.3.5 Comments

The experimental group made several useful comments about the VR system:

- Most participants felt more assured during post-test, although they did not generally feel that they had mastered the technique;
- The forces exhibited by the simulator felt weak sometimes;

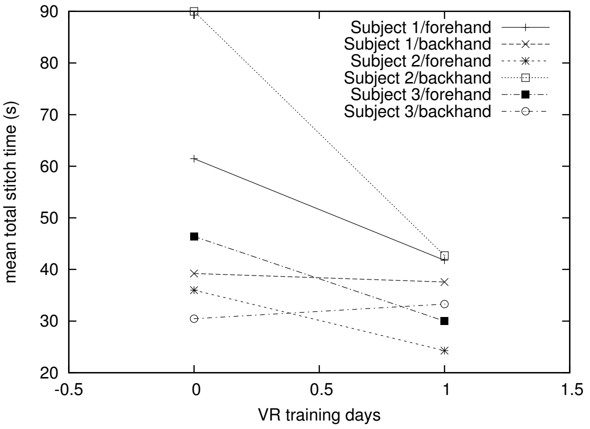


Figure 7.14: Mean stitch time in the simulator

- Some feedback relating to time taken would have been helpful, relating to the most error-prone region of the suturing action;
- Piercing the mesh seemed to get more difficult through practice and this problem was not overcome during the test;
- The exit point seemed to be difficult to predict or correct from the path anticipated at entry;

Many of the points raised here seem to be related to insufficient time spent in practice — most appeared to feel that, despite some level of improvement, they had not mastered the technique. See Section 7.5 for further discussion.

7.4 Test C: Usability study

7.4.1 Introduction

It was originally intended that this study should comprise a quasi-transfer and retention test of surgical trainees, taking place over 3–4 sessions. Although, initially, this was thought to be feasible entirely on a voluntary basis, in practice, the demands of surgery schedules prevented its completion. To complement the transfer study, however, a more qualitative study by questionnaire was proposed, to be updated after each session. The introductory session was intended to be fairly informal and allow people to get used to the equipment. Forces were deliberately set to be fairly weak, with the bi-phase model generating greater forces after a modest displacement (3 mm), so that users would be less likely to be daunted, especially if the capacity of the system was exceeded. All participants had a brief explanation of the task and how to use the apparatus to start trials, set the needle etc.

7.4.2 Objectives

Since it did not prove to be possible to obtain repeat tests, the primary aim of the study was to obtain a qualitative assessment of the *FESTIVALS* system by clinicians. Since data was obtained across a range of expertise, however, it was also possible to obtain statistics for general comparison across the groups and the tests above.

7.4.3 Method

Participants

15 clinicians, from various disciplines, participated in the test — conducted at St James' Hospital, Leeds — on a voluntary basis. Of these, 12 returned completed questionnaires. Data were only excluded from one of the non-returning participants, however, since groups for the others were able to be determined later. The participants therefore comprised:

- Surgical:
    - 6 trainees/SHOs, in the 3rd/4th year of rotation (5 males, 1 female; age: 25.5±1.7 years);
    - 2 specialist registrars (SpR year 6, both male; both age: 37);
    - 2 vascular consultants (both male; both age: 46);
- Microsurgical:
    - 1 consultant (male; age: 58)
- Non-surgical:
    - 3 consultant radiologists (male; age: 48.5±6.3 years)

All subjects were right-handed, except for one specialist registrar. Two of the participants (a registrar and vascular consultant surgeon) had helped in the development of the *FESTIVALS* system, and therefore had some experience of the task several months prior to this exercise. Otherwise, most subjects had some experience with video games, but very little experience of VR devices. The microsurgeon was treated separately here as the instrumented PHANToM was much bigger and heavier than his usual working tools (although for some analyses these results were combined with those of the other consultant vascular surgeons).

Task

The subjects undertook a session of 15–30 minutes using their preferred technique with the semi-cylindrical model of Figure 5.16(a). Many of the participants were bleeped to return to theatre during the session, but all participants managed to completed at least one 3-minute VR trial.

The needle driver was initially attached to the PHANToM using the second form of attachment (see 5.3.2), but unfortunately, the wiring broke on the first day of testing and the other form of mounting was used from then on. As the needle holder was then mounted to the right-hand side of the PHANToM, the left-handed registrar volunteered to work with his right hand. Having used the system previously, the latter was also persuaded to attempt the bimanual task with the longitudinally cut cylindrical model of Figure 5.16(b).

The questionnaires contained ratings on a 4-point Likert scale, a copy of which is included in Appendix refappx:questionnaire.

Analysis

The data were analysed on the basis of the groupings shown (SHOs, SpRs etc.) except for the registrar who worked with his NDH, who also provided data for 1 and 2-handed working. ANOVA tests were conducted with ‘R’ as described above. Since the session times were relatively short, it was interesting to observe how well the interface was mastered. An indication of this was assumed to be the divergence of the error data and the occurrence of more erratic error features. So that the more erratic data did not bias the plots given here, however, error-bar plots were eschewed in favour of boxplots (showing median, interquartile range and ‘erratics’ as before), without the exclusion of data.

7.4.4 Results

7.4.4.1 *Questionnaire data*

The ratings from the completed questionnaires from all the tests are given in Table 7.3. In general, the feedback from this initial test was positive, but with several criticisms:

1. *PHANToM:* most users found the instrumented PHANToM felt heavy and awkward, especially to begin with. Most appeared to cope well with the opening/closing of the device, but several people found grabbing the needle awkward.

2. *Graphics:* Assessing depth was reported as an issue by several subjects, although the average score attributed here appears reasonable. Many people also found it difficult to place themselves in the scene (ie. they were ‘lost’) but were usually alright when the needle etc. was located.

3. *Forces:* this was the severest criticism that most people made, although the tabulated score is still ‘fair’ — the forces felt weak or unrealistic to several people. In fact, although realistic parameters were used in the model, the forces were deliberately made to be fairly soft, so as to reduce the potential for instabilities, especially where people were unused to the system (see 8.3.2).

4. *Spacemouse:* relatively few people tried to use the device to manipulate the probe, largely as time was not sufficient. When used to set the needle etc. many people found the device relative easy to learn.

The participants also made several useful comments on the questionnaires:

- The forces exhibited by the system felt weak especially when entering the ‘tissue’, and sometimes felt rubbery.

- Most users reported that the haptic device felt heavy, though some said that they felt more familiar with the forces generated towards the end of the session.

- A scoring system is needed which should perhaps be capable of relaying: (i) time taken, (ii) successful passes and (iii) maximum angular speed.

- It might be useful to model the expected curve of the needle.

- The system encouraged a posture which was not correct.

How did you rate?	Test A	Test B			Test C												Mean
	-	1	2	3	Trainee				SpR		CS		MS	NSC			
Needle holders:	2	1	2	1	2	2	1	-	1	1	2	2	4	2	2	2	1.8
- mounting	1	2	3	2	3	2	1	-	1	3	2	1	2	2	2	3	2.0
- opening & closing	1	4	2	2	2	1	1	-	1	1	1	2	3	1	2	2	1.7
- physical rotation	2	2	4	3	3	2	1	-	1	2	2	3	2	2	3	2	2.3
Graphics:																	
- stereo & depth cue	3	2	2	2	2	1	1	-	1	1	2	2	-	1	2	1	1.6
- rotation on screen	1	3	2	1	3	3	1	-	1	1	1	2	-	1	2	1	1.6
- mesh deformation	1	1	2	3	3	2	1	-	2	3	2	2	-	2	2	1	1.9
- probability of getting lost	1	1	1	1	3	2	1	-	2	2	3	3	-	2	1	2	1.8
- feedback of planes/spheres	1	2	2	3	2	2	1	-	1	1	3	2	-	2	3	2	1.9
Force feedback:																	
- quality	1	2	2	3	-	2	2	-	3	3	3	2	3	2	1	2	2.2
- biphase model	na	na	na	na	-	-	1	-	4	2	3	2	-	-	2	2	2.3
- workspace	-	3	2	2	-	-	1	-	1	1	3	2	-	-	2	2	1.9
Spacemouse:																	
- for setting needle	1	3	1	1	3	2	1	-	2	2	-	3	-	1	-	2	1.8
- for setting stereo	1	3	1	1	3	-	1	-	2	-	-	3	-	-	-	2	1.9
- joystick for probe	1	-	2	1	3	-	1	-	2	2	-	2	-	-	-	2	1.8
Scores: 1=Good/High, 2=OK,3=Fair,4=Poor/Low.																	
Test C: SpR=Specialist Registrar, CS=Consultant Surgeon, MS=Microsurgeon, NSC=Non-surgical Consultants																	

Table 7.3: Questionnaire scores from Tests A–C

- The system should help with practice by the NDH.
- The feedback given by the planes was helpful.
- The visual feedback was impressive and helped to create an 'enjoyable challenge'.

See Section 7.5 for further discussion of these points.

7.4.4.2 *VR simulator assessment*

Given the exploratory nature of the test, participants were permitted to chose which technique to attempt. In practice, most subjects adopted techniques they were comfortable with, the most basic forehand/forehand technique being the most common, whilst the more senior surgical staff tended to try more complex skills with targeting such as forehand/overhand grabbing. This variation in practice may have acted to reduce significant differences, but does give some insight into the range of techniques which the simulator might be required to represent.

The metrics discussed here are identical to those for Test A (7.2). For all the plots, the DH groups are denoted as: SHO (Senior House Officer), SpR (specialist registrar), CS (consultant surgeon), MS (microsurgeon) and NSC (non-surgical consultants). For the NDH, two groups are represented for the unimanual (1h) and bimanual (2h) conditions. Results from some of the Test A trials (the 1st, 14th and 43rd) are also presented here for comparison and are discussed further in Section 8.3.1.

1. *Plane angular error*

    - Figure 7.15 displays a boxplot of the difference between average planes of entry and exit. Although the more highly trained groups appear to have smaller variances, this may be due to the smaller numbers involved in the non-trainee groups and is not significant. The average error across all groups was 11.5° and the median was 9.2°, suggesting that a figure of around 10° may be acceptable, at least for this apparatus. However, it also notable that several individuals achieved an average of c.5°.
    - An unexpected result of this test is that the NDH conditions show significantly lower errors than the remaining groups at the $p < 0.05$ level (in Welch t-tests).

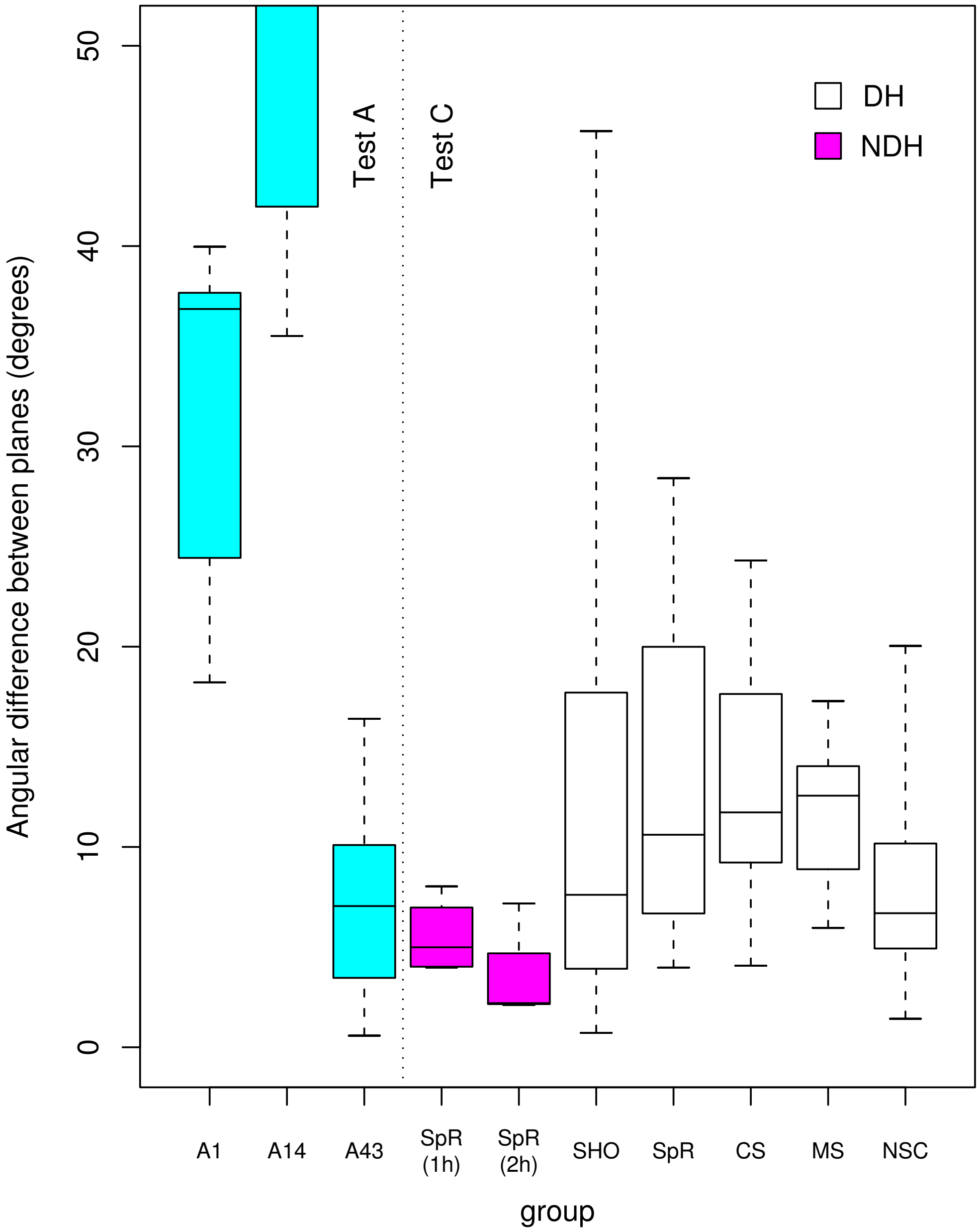


Figure 7.15: Difference between entry and exit planes

2. *Strike angle*

   - Figure 7.16 shows boxplots strike angle error (to the surface of the mesh). All groups show wide ranging, erratic data, suggesting some difficulty adapting to the interface. Significant differences are revealed between the groups, notably between the trainee and specialist registrar groups, but this is probably artificial, since some trainees demurred from targeting the beads along the edge of the wound. The variation present in the data suggests that an error of 20° (DH) or 30° (NDH) may be acceptable.

3. *Edge direction error*

   - This data also shows a high level of variation, Figure 7.17, with a suggested figure of 20° error as an acceptable margin. Note that the bimanual condition seems to increase the error for the NDH, but that this is not significant (when taken as an average error over the whole phase — to remove timing factors, see below).

4. *Needle centre movement*

   - The average displacement of each sampled position from the computed mean centre indicates that a variation of 1–2 mm is acceptable, with no significant difference between the groups, except for the bimanual condition. For the latter, a (Welch) t-test between the 1-handed (1h) and 2-handed (2h) tests shows a significant improvement in using both hands ($p < 0.001$). Figure 7.18 shows the distribution of these average displacements from centre for each group.

5. *Distance between centres*

   - Figure 7.19 displays a range of errors here, with a mean value of 2.8±1.2 mm, with no significant differences between the groups.

6. *Principal Components Analysis (PCA)*

   - Figure 7.20 shows a relatively consistent out-of-plane errors during both phases of needle insertion, but with a significant difference between the phases (insertion mean 31.8°, retrieval mean 38.2°; $p < 0.01$). Note that these error levels are comparable with those achieved during Test

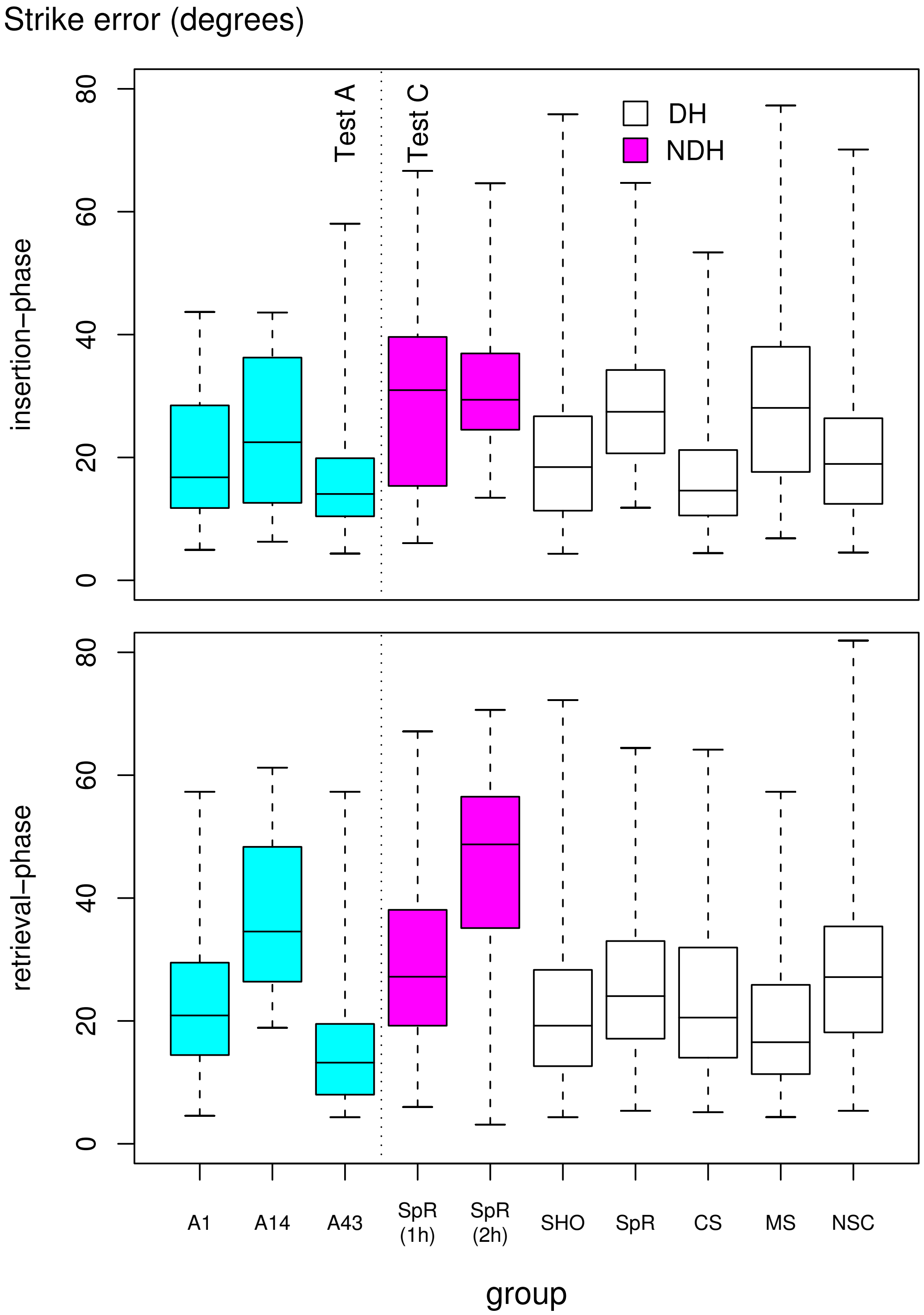


Figure 7.16: Strike angle error

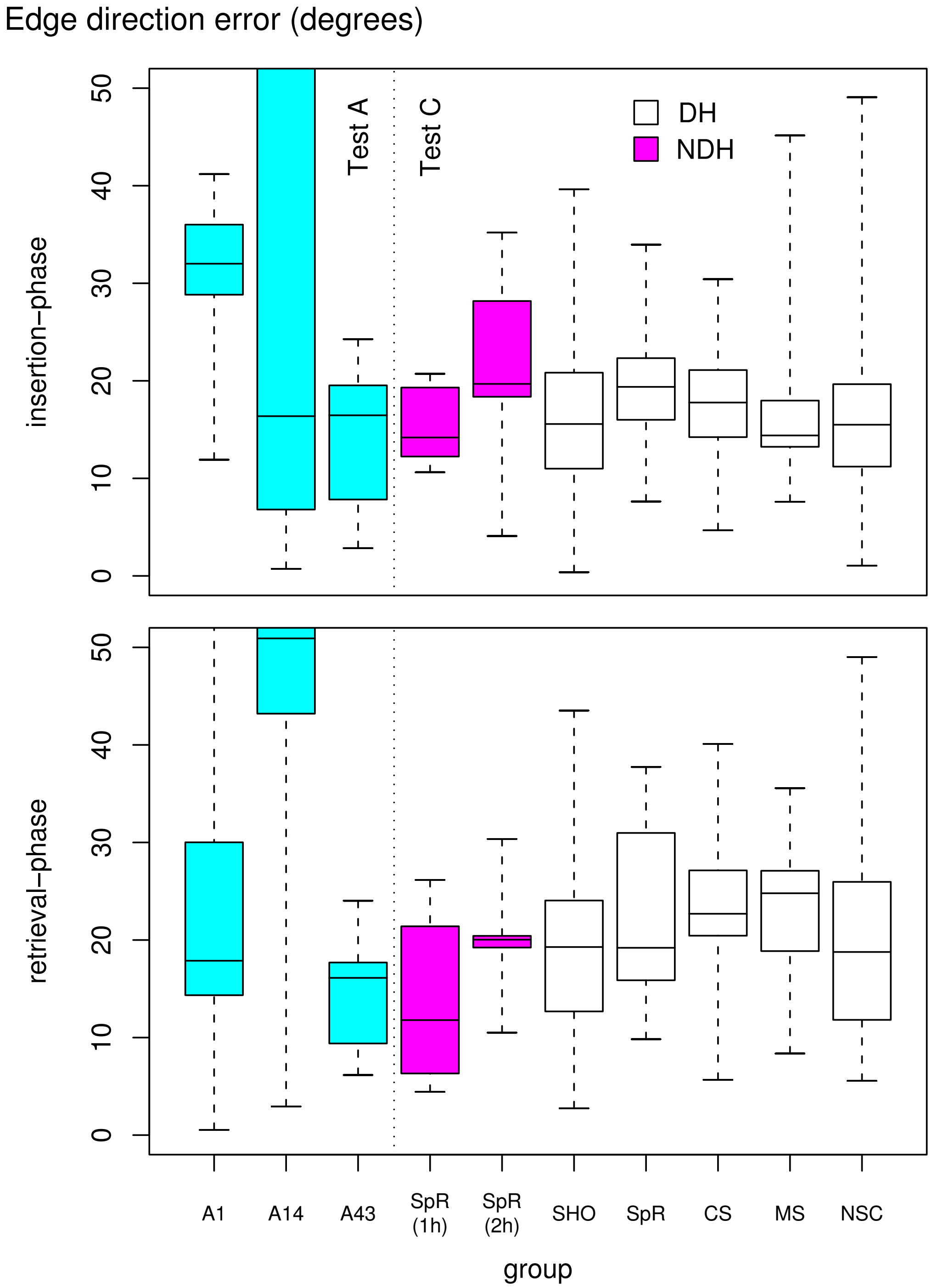


Figure 7.17: Edge direction error

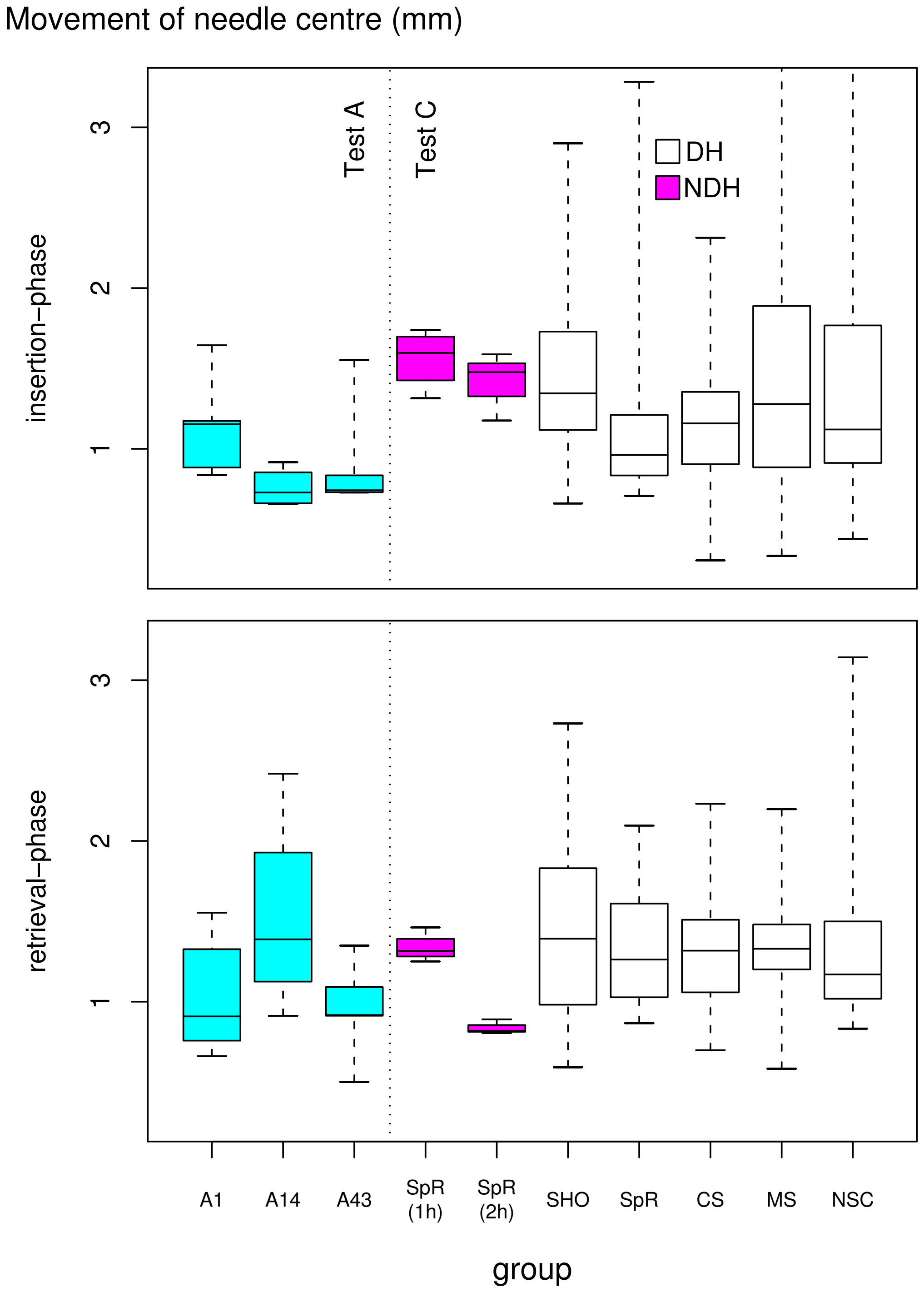


Figure 7.18: Movement from the mean centre

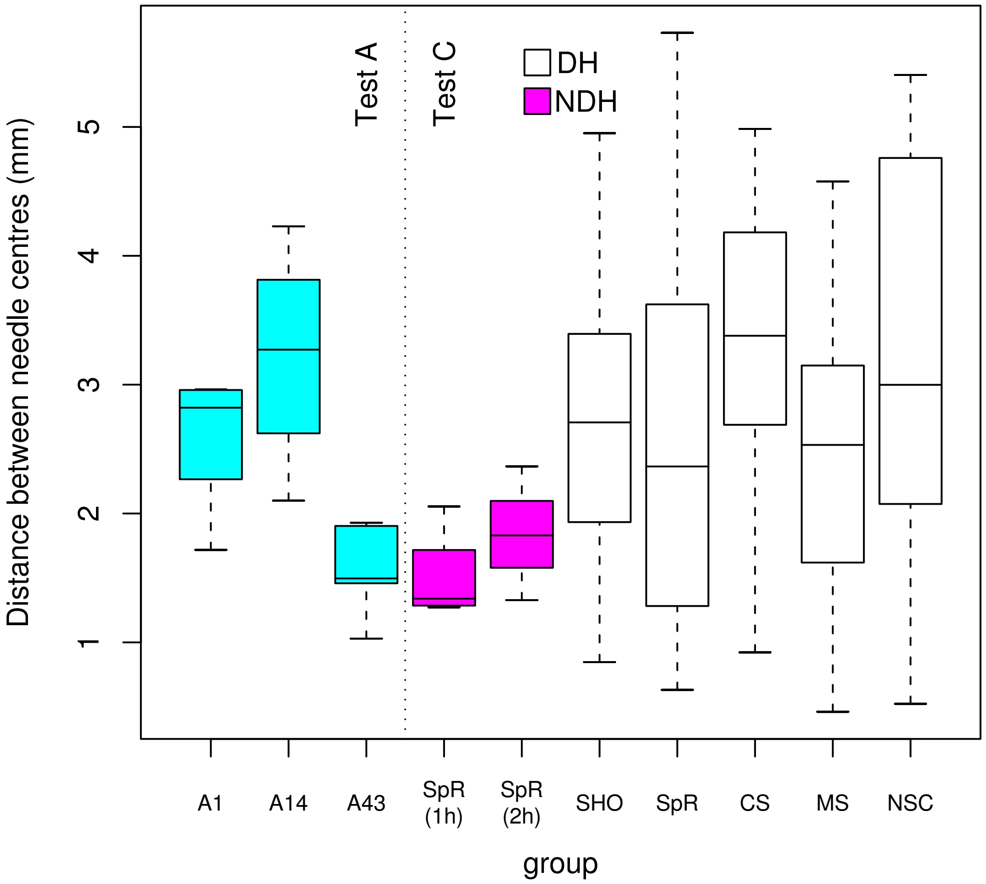


Figure 7.19: Distance between entry and exit centres

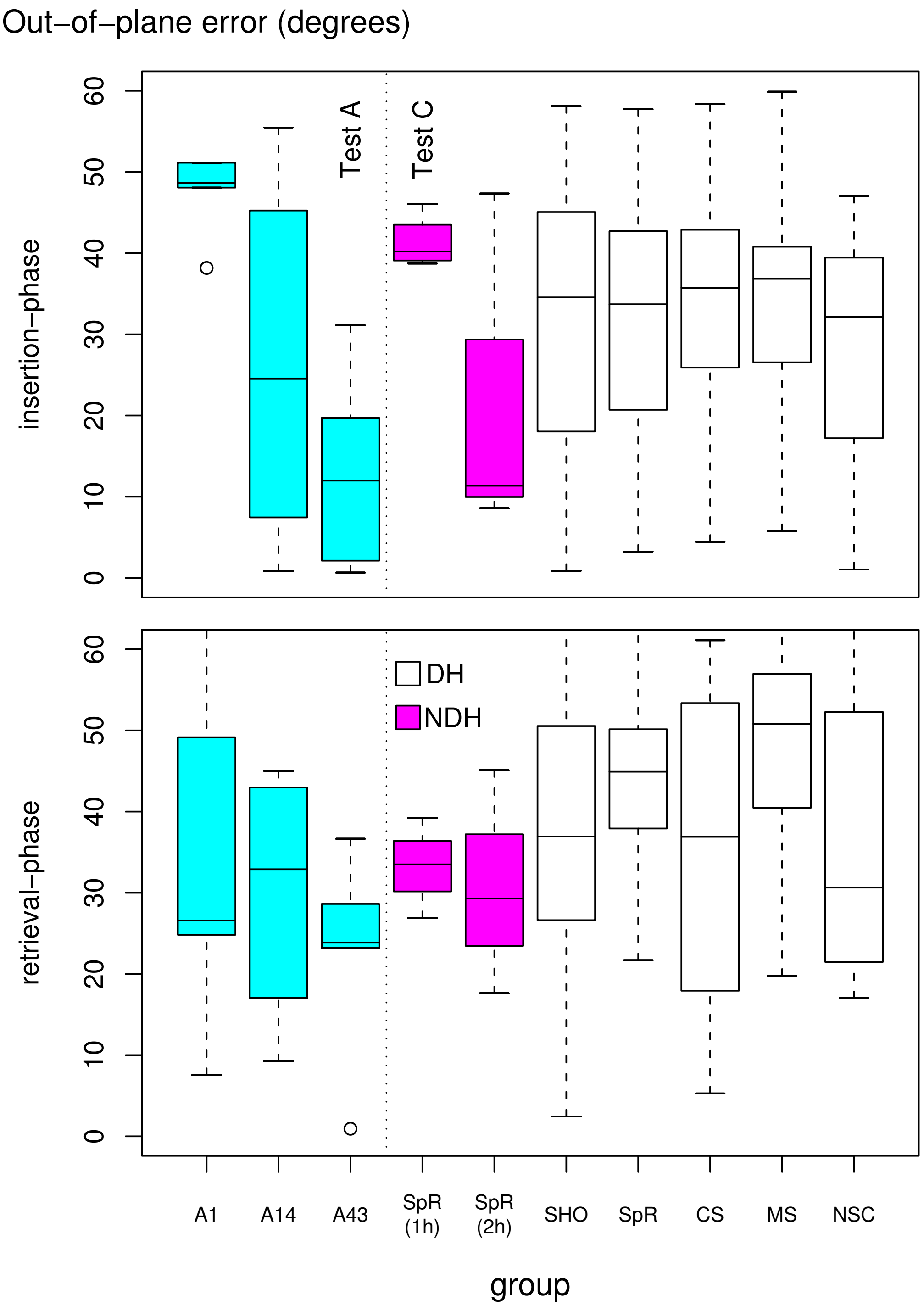


Figure 7.20: Principal components analysis

A. There is a small but non-significant improvement between the NDH conditions, when using both hands.

7. *Movement efficiency*

   - Figures 7.21 and 7.22 show the total displacement of the PHANToM endpoint and time taken for passing the needle through the vessel. Several points are noteworthy:
   - There are significant differences between consultant surgeons (CS and MS) and SHOs during the insertion phase (time $p < 0.01$; displacement $p < 0.001$) indicating that *construct validity* holds for this metric especially during this phase. However, there were no significant differences between these groups for overall or inter-stitch time (including the groups with the NDH condition).
   - The use of both hands has a striking and opposing effect during insertion and retrieval, the former taking longer and requiring a greater displacement to set up the alignment of the needle, but with a corresponding speeding up effect during retrieval: the two-handed conditions are negatively correlated with $r^2 = -0.997$, $p < 0.05$ for displacement (this correlation is not significant for time taken, but note that there is only 1 dof).

8. *Maximum applied forces*

   - Given the earlier disparity observed with regard to forces exerted (Section 2.4.3.4), Figure 7.23 displays a boxplot of the maximum magnitude of force response registered by the system. It is difficult to interpret these data clearly, since the use of a velocity threshold for determining puncture felt unrealistic to some of the clinicians tested and would have tended to increase force responses. Interestingly, the Test A data and the bimanual condition show non-significant decreases in force response, perhaps reflecting some degree of accustomisation to the choice of threshold.

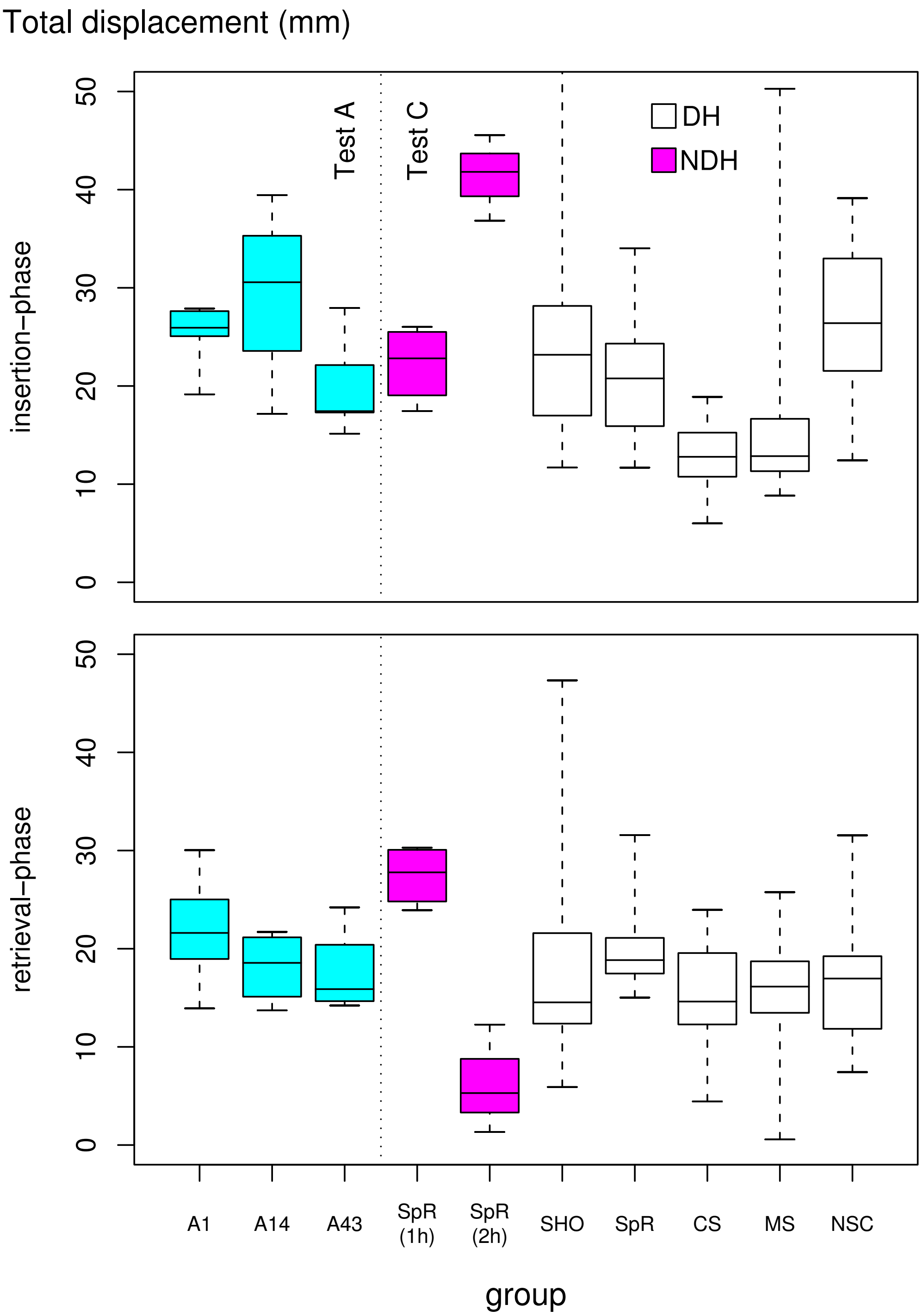


Figure 7.21: Movement of the PHANToM endpoint

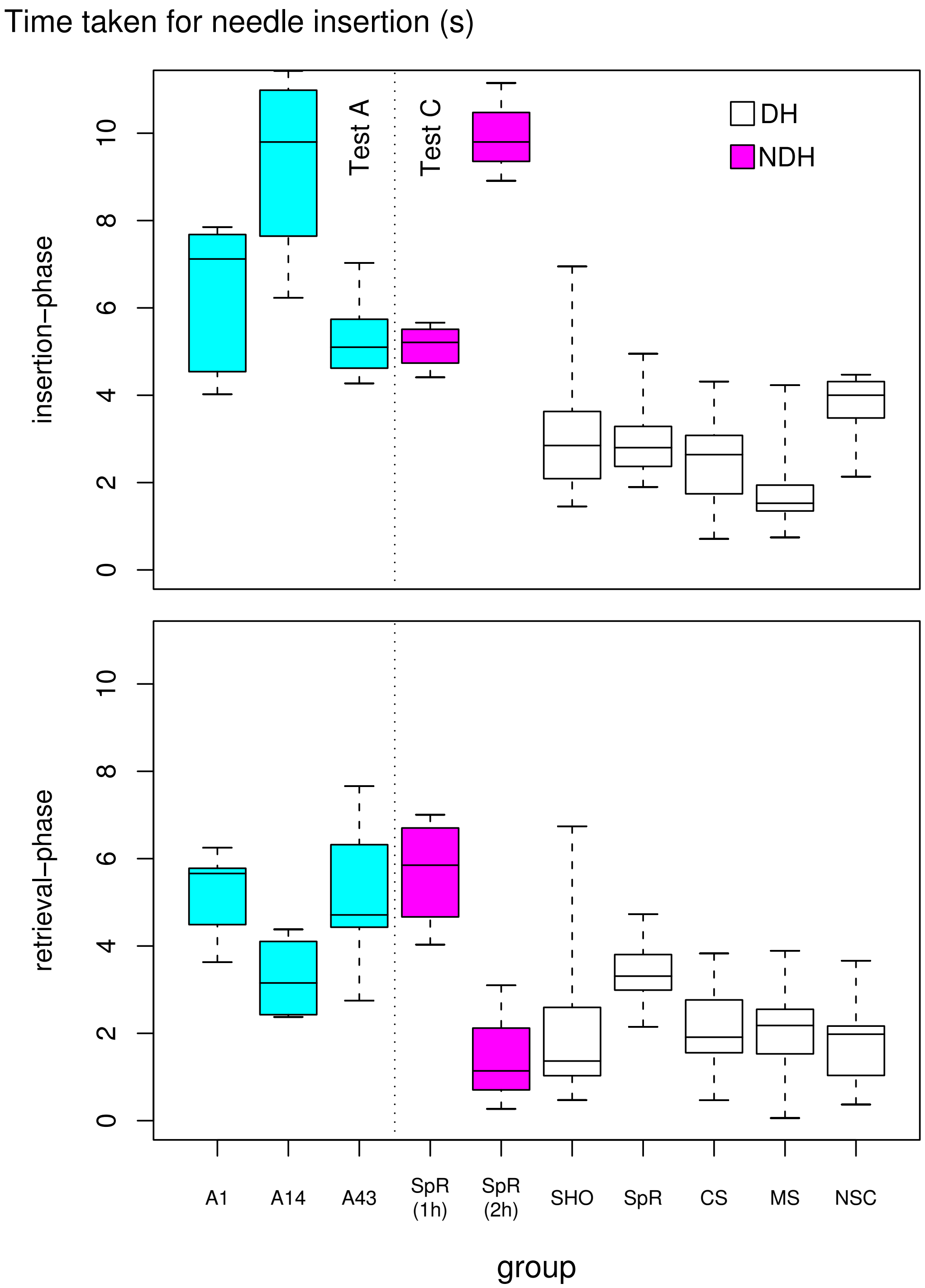


Figure 7.22: Timing of needle insertion

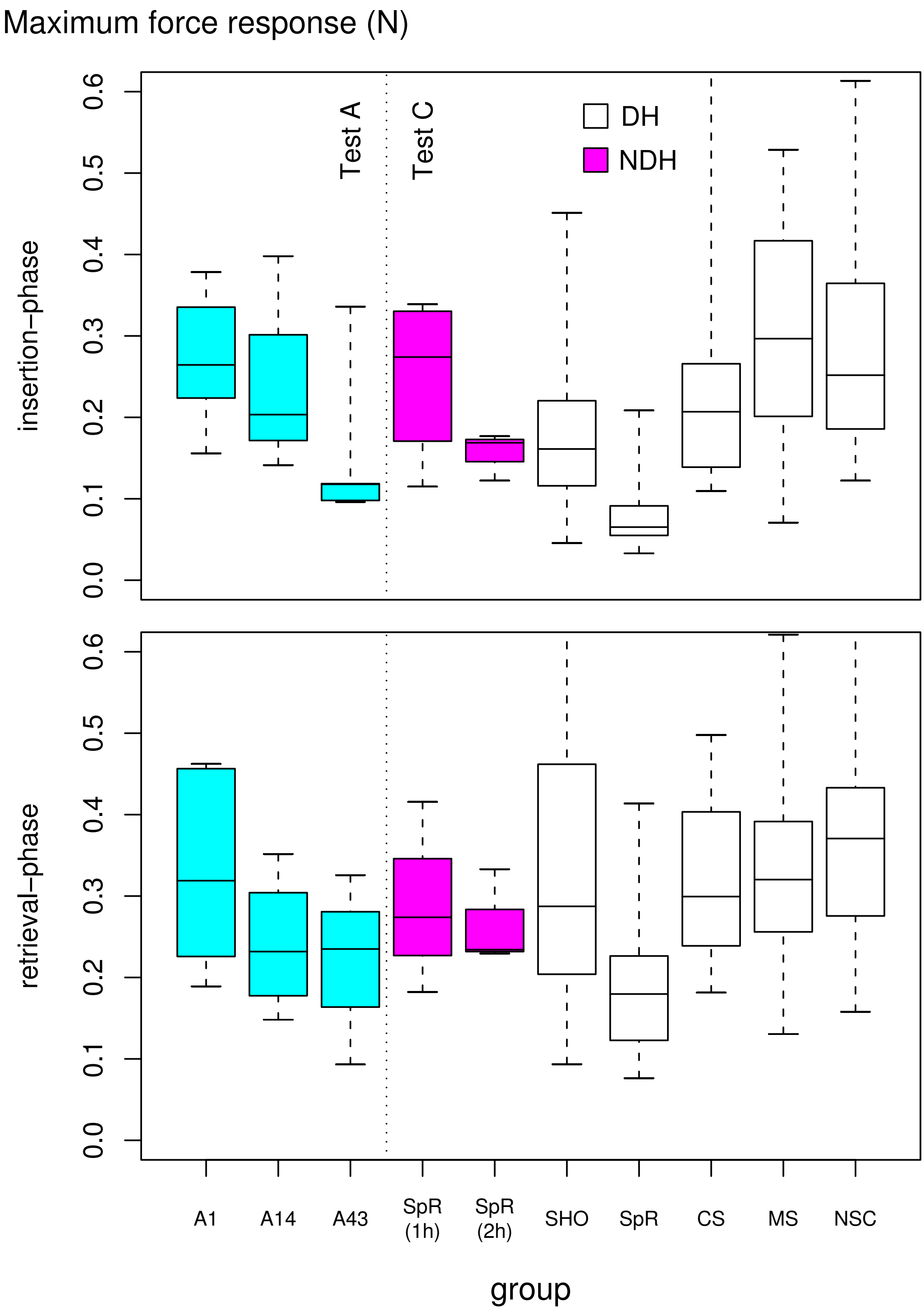


Figure 7.23: Maximum force response

7.5 Summary of test results

7.5.1 Test A: Learning curve

Hypothesis test results:

The results presented above allow qualification of the sub-hypothesis introduced in Section 7.1.2, as follows:

H_A: Performance showed a complex learning curve with significant improvement in terms of error reduction, and, at least for this training model, many of the errors identified were brought to within a comparable region to expert performances measured during Test C. Performance was also retained during retention tests, nearly 6 weeks later, hence demonstrating consistency and persistency.

Discussion:

Since only one individual took part in this test, it is difficult to generalise to a wider population but the results do indicate improvement over time with six hours' training in as many sessions. The improvement in performance was linked to reduced error scores, increasing consistency and was retained for a period of at least 40 days. This was *not* a straightforward improvement, however, but appeared to comprise three phases:

1. An initial phase of little or no real change, which continues for several sessions;
2. A second much more chaotic phase, with a diverse range of error scores from one trial to the next;
3. A final phase in which there is a good degree of consistency between adjacent scores, and performance seems to have arrived at plateau. The final level of performance was often close to that of the clinicians in Test C (Figures 7.15–7.22) and indicates some degree of equivalence at least for this test.

The form of these phases suggests that existing pre-conceptions and 'programming' might need to be 'broken' before new learning can take place. This view is consistent with the various learning stage models developed by motor psychologists (see 3.5.4). Breaking 'old habits' sometimes requires many practice trials, during which performance may be highly unstable [267, p. 216]. Alternatively, it may be that various strategies were being tested in a cyclic fashion, in the manner suggested by Nourrit *et al* for skiing simulation (Section 3.5.9.2). Whatever the root causes of these phenomena, it is clear that these phases of learning are poorly described by linear or random effects models and that unless specific care is taken, statistical analyses may be inappropriate. In particular, it would seem to be necessary to run tests over a sufficient length of time, preferably with a well-matched control group.

Before a deeper understanding of the effects of simulator training can be achieved, however, it would seem that research to validate learning models must be made a greater priority (see 8.2.3).

7.5.2 Test B: Using real tools

Hypothesis test results:

H_B: Performance on the simulator did not produce significant improvement using real-world tools; although some improvement in suturing was indicated, this was not sufficient to outweigh the practice effect of testing (at least to the point of significance).

Discussion:

Although non-significant, the test provided data to assist with possible future investigations by allowing a prediction of power based on the variances obtained. In looking at the results from Test A, it is also likely that power would have been greatly improved by doubling or tripling the number of sessions. A major difficulty with this type of test, however, is the problem of assessing the quality of sutures below the surface of the pad and it is not clear how this might be remedied in future, unless testing is performed with tracking devices (see 2.2.3).

7.5.3 Test C: Usability study

Hypothesis test results:

H_C: The performances of clinicians did not violate the property of *construct validity*, which was, in fact, demonstrated to hold for some efficiency metrics — time taken and distance moved (during insertion).

Discussion:

Despite some important criticisms, mainly in relation to force rendering and the weight of the instrumented PHANToM, the system was well-received by the majority of clinical staff and all respondents accepted the potential benefit to training. Use of the NDH tended to increase errors and time taken, which suggested that some loss of performance was acceptable in situations where the DH was unable to reach. The bimanual condition had a significant effect upon performance, increasing the time taken, but sometimes significantly reducing errors (even compared to DH groups).

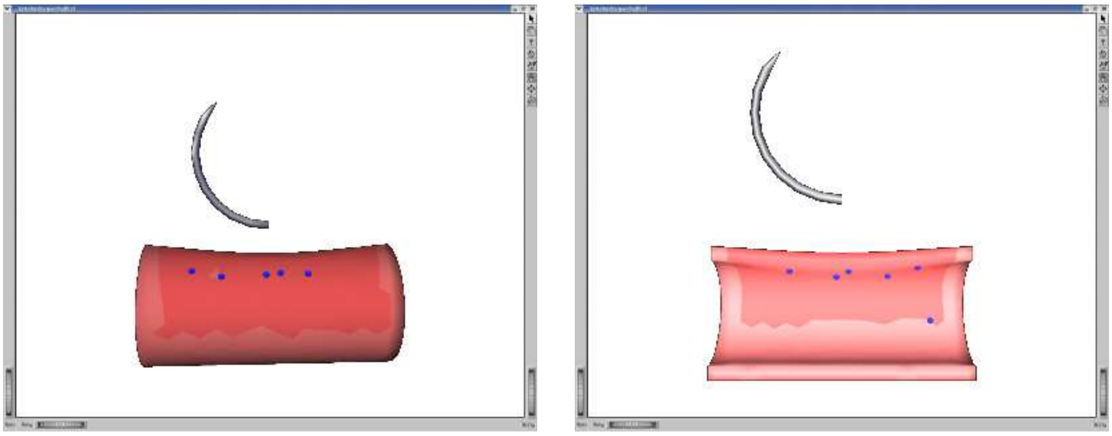
A striking feature of the consultants' performance was that it was generally much faster than the remaining groups over the critical period of needle insertion. Overall time taken was not significantly different, suggesting that more time was spent in preparation. This point is discussed further in Section 8.3.1, but since errors are not significantly different, the implication would seem to be that there is a strong element of technique involved.

7.6 Developing a scoring system

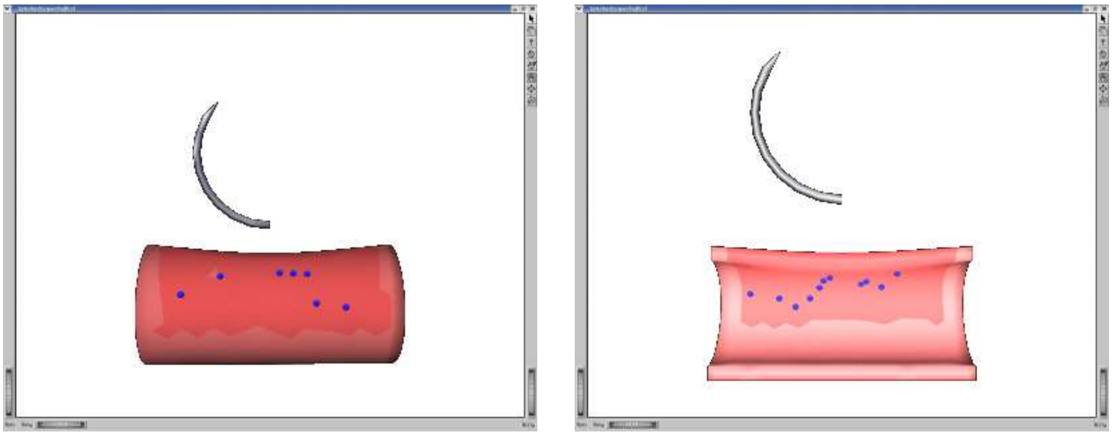
7.6.1 Scoring and feedback?

Data on time and displacement parameters were deliberately withheld during the evaluation tests to emphasise specific feedback on errors (using the graphical display). This was sufficient to promote learning in Test A, but a number of clinicians commented that some form of scoring system was also required.

During Test C, it was also observed that the fastest trainees tried to adopt a fixed arm/wrist position which suggested some indifference to the task. In fact, their behaviour suggested a reduction of the task by first establishing a comfortable working position in front of the PHANToM and then probing the mesh until the correct angle of approach was found, Figure 7.24. This (eventually) allowed fast movements with low error scores, but since targeting skills were not being acquired, these successful results would not have been likely to transfer to other suturing tasks. In hindsight, therefore, the decision not to reveal timing information would seem to have been correct, but the absence of a target-related score was a serious omission.



(a) Consultant performance for one trial



(b) Trainee/SHO performance for one trial

Figure 7.24: Targeting issues

7.6.2 A score for targeting

In Figure 7.24, it can be seen that the first insertion attempt by the consultant appears to be awry but is understandable on the basis of the novelty of the equipment. On the other hand, the many insertion attempts by the SHO suggest a lack of appropriate care when taking aim. Attempting to define the symmetry/spacing of the resulting pattern presents a similar problem to that observed during Test B. In this case, however, both internal and external data are readily available and so the issues can be more easily defined. At least three problems may be identified: (i) the scattering of insertion points due to probing etc; (ii) the bunching of sutures near a given point, which would have been likely to weaken real tissue severely; and (iii) inconsistent distances between sutures or along the edge of the wound.

For the scattering problem, an error score can be derived by approximating the area of the spread of stitches by ellipses, ϵ_{ext} and ϵ_{int}. For the latter, the major and minor axes will be the extents of the insertion points along the principal axes of Figure 7.24. For the bunching problem in (ii), since the target beads are 2 mm apart, stitches placed at a distance $d < 1mm$ will incur a penalty of $(2 - d)^2$. For (iii), since the edge depth, e, of the target beads was defined to be 2.4 mm, a penalty will be incurred as the square of the deviation from this figure (external side only, since suturing technique permits smaller edge depths to the internal face — see Figure 5.3). In addition, 5 sutures were expected: the difference between the number of stitches to the internal and external faces (N_{int} and N_{ext} respectively) will incur further penalties as the square of the deviation. This leads to a 7 term error coefficient as:

$$\begin{aligned} Target\,error &= \omega_1 \left[\epsilon_{ext} + \epsilon_{int}\right] + \omega_2 \left[\Sigma(2 - d_{ext})^2 + \Sigma(2 - d_{int})^2\right] \\ &\quad + \omega_3 \left[\Sigma(e - 2.4)^2\right] + \omega_4 \left[(N_{ext} - 5)^2 + (N_{int} - 5)^2\right] \qquad (7.1) \end{aligned}$$

It is immediately apparent that one problem with the construction of such terms is the problem of normalization, ie. the choice of weights, ω_i. If the data have been collected, this is relatively straightforward since standardised ‘z-scores’ or normalization between the maximum and minimum can be used. During or after particular exercises, if a score is required, it would be necessary to use pre-determined weights. A further paradox of any such scoring scheme is that it needs to be simple enough to grasp readily, robust to noise and yet (ideally) sensitive enough to detect improvements, on, say, adjacent test scores.

7.6.3 Preliminary results

As an early discrimination test of the targeting coefficients outlined, Figure 7.25 displays a pairs plot with groups separated by colour. It should be noted that given variations in the techniques adopted and the short period of testing, the level of discrimination would not be expected to be perfect. Several features are, however, of interest:

- all the error coefficients isolate those individuals who did not aim carefully;
- the registrar who used the NDH to perform the tasks is weakly isolated in the unimanual condition, but is strongly separated in 3 out of 4 error terms in the bimanual condition (the exception being with respect to 'bunching');
- the consultant groups are generally well-represented in the region of the lowest errors, whilst the trainees display a spread of errors across a broad range. The trainees who did not target the needle as intended are well discriminated, as intended.

Given the limitations of the data, it would be unwise to comment further, but it is possible to see that the plot gives a straightforward method of selection of the weights, ω_i.

7.6.4 Towards an overall score

Further discussion on combining individual error scores is given in Section 8.2.3, but time precludes developing or testing an overall scoring procedure here. It is suggested, however, that this might be achieved along similar lines, combining angular and target-related scores into a unique index. It may also be that timing information should also be made available, but perhaps only at the end of any given session, so that testees are not tempted to 'race against the clock'.

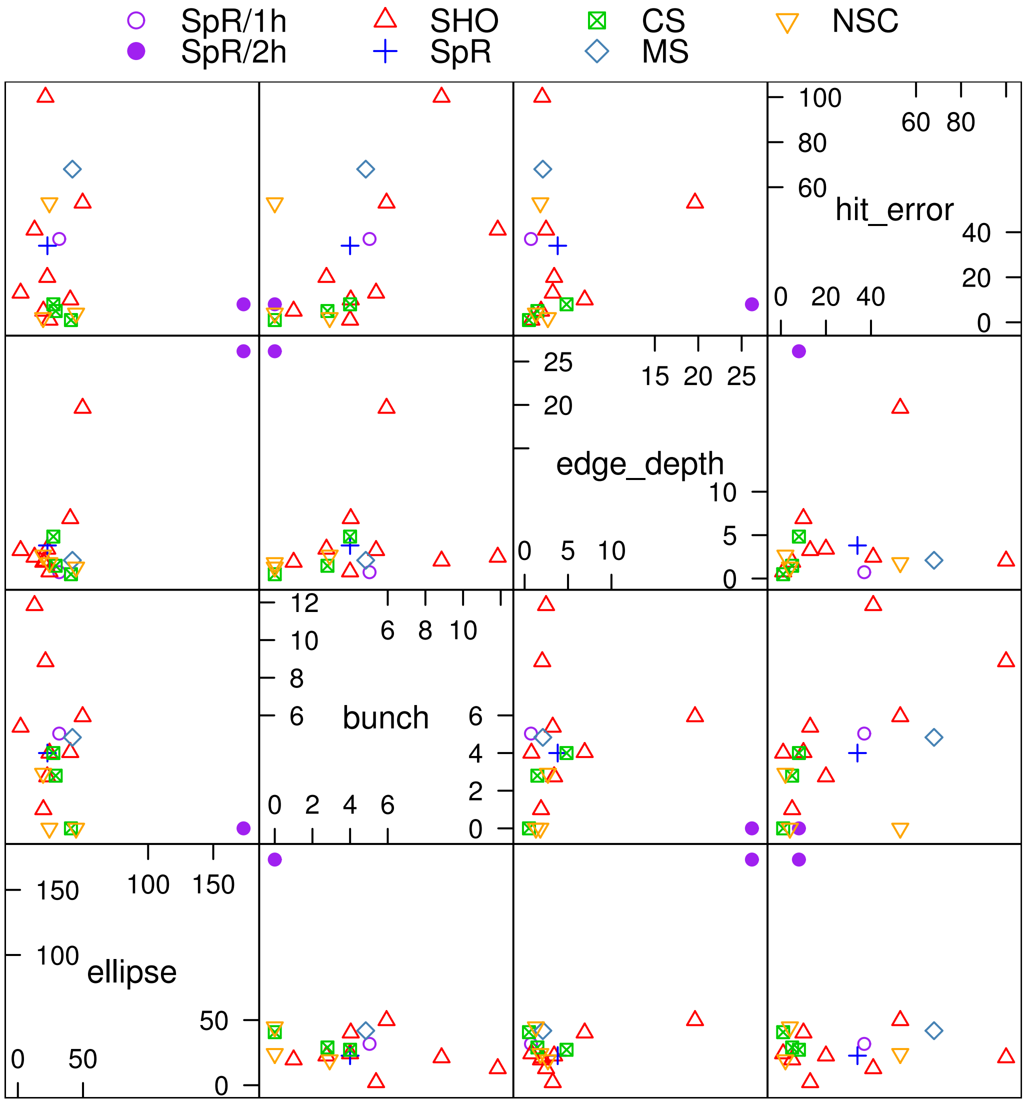


Figure 7.25: Target error discrimination plot

where:

SHO=Senior House Officer, SpR=Specialist Registrar, CS=Consultant Surgeon (vascular), MS=Microsurgeon and NSC=Non-Surgical Consultants. For the NDH, two groups are represented for the unimanual (SpR/1h) and bimanual (SpR/2h) conditions.

Chapter 8

Discussion

This chapter gives a review of the present findings with respect to surgical simulation, beginning with a synthesis of previous chapters (Section 8.1). The synthesis builds a critique of *construct validity* testing in the simulation literature. Data from individual performances are then re-examined to attempt to develop an understanding of error control in relation to surgical technique ie. towards a model for motor learning (Section 8.2). The chapter closes by addressing the limits of the present investigations and making recommendations for future work (Section 8.3).

'Above all else show the data.'

> - Edward R. Tufte, *The Visual Display of Quantitative Information*, 2001

8.1 Synthesis

8.1.1 Motivation

Despite proposals to shorten surgical apprenticeships, which are to be fully introduced by 2005, the medical profession has yet to find adequate methods of accelerating the training of junior doctors. In other industries where highly technical skills must be acquired, this problem has been addressed by the development of simulators to give standard training drills. In surgery, however, convincing simulations have yet to be fully realised, let alone certified, and this problem is compounded by the many forms of specialisation which surgery can take (vascular, cardiac, radiology etc.). As a consequence, instead of standard interfaces in which, say, pilots may transfer skills from one aircraft to the next, a range of simulations are needed with any number of models to represent potential complications and disease.

8.1.2 Assessing simulators

The development of MIS and interventional techniques in the 1990s led to a public outcry about skills training in the medical profession. The resulting debate provided a good opportunity for VR researchers to create and test surgical simulators as the interfaces were relatively straightforward to reproduce. But although several commercial simulators have now been developed, the cost of VR systems to teaching schools still remains an issue and few have enjoyed medical endorsement. Hence there is an urgent need to establish the potential benefits of simulators. A further problem, which seems to complete a vicious circle, is that the evaluation of these systems requires the input of health professionals, who are neither able to commit long periods of time to assessments, nor willing to put patients at an unnecessary risk.

This situation has resulted in the development of various ‘home-grown’ methods of surgical simulator assessment (surveyed of Chapter 2). Some researchers, for example, have favoured dexterity tests (eg. using ADEPT, ICSAD) and have been able to show concurrency between tests and independent clinical assessments. However, factors such as age, sex and handedness weaken the reliability of these tests and other research has shown that even modest amounts of training tends to blur distinctions between measured ability levels.

Instead of longer term transfer or retention tests (8.1.3), many researchers have preferred the quasi-experimental approach of establishing *construct validity*. This might be expected, given, as noted above, that surgeons usually have heavy commitments. All too often, however, it appears that researchers have applied the *construct validity* test without further analyses, as if good discrimination between experts and novices is a useful endpoint in itself. A little reflection shows that this is not so: experts are expected to be more capable than novices and a favourable result only proves that the system under test has not distorted this fact.

A more appropriate experimental design might, say, randomize experts and novices into an unknown order of testing (with appropriate blinding to the test organisers) to see if the simulator can then discriminate the expertise of participants into realistic classes. If retention tests or blinded experiments seem too costly to implement, researchers should, at the very least, ask whether *construct validity* holds for a definite period of time. The BDI study of O'Toole *et al* [308], for example, preserved significant differences between the expert and novice groups during the hour-long test of each subject. The estimate given here (Section 3.5.5), however, suggests that significant differences might have evaporated after a few more hours' practice. Should novices be considered experts after this time? If not, the question arises as to whether this test has achieved anything at all.

These modes of assessment contrast sharply with the recommendations of aviation researchers, where results may be considered meaningless unless issues of reliability have been considered. In surgical simulations, the effects of repeated testing are usually ignored and corrections for sphericity and multiple significance tests are generally overlooked. Worse still, misconceptions about the nature of null hypothesis statistical tests (NHST) are rife. Few researchers have shown any appreciation of the concept of *statistical power* and have often equated non-significance with support for the null hypothesis. Equally, they have obtained data from hundreds of participants in what critics of NHST would see as a bid to exaggerate otherwise meaningless differences (see 8.2.1). A brief summary of assessments of the MIST-VR system (to date, the most thoroughly tested) will hopefully be sufficient to give a synopsis about progress in this field:

- The study by Paisley *et al* demonstrated that bench models were superior to MIST in discrimination tests between experts and novices, but the retest phase showed more gains by students and trainees on MIST than on any other device [310]. This would seem to suggest that the MIST system possesses stronger properties for training than for assessment (2.4.4.3).

- The later study by Gallagher *et al* used a very large sample population and was able to demonstrate construct validity, although not all experts performed well [170].

- Torkington *et al* showed that Basic Skills instruction was found to be as effective as MIST in a transfer test to a box trainer [420].

- Students who trained for three hours on MIST did not perform noticeably better in the appendectomy of a pig [34].

- Using a regular training regimen of one hour per day for 8 days (to a preset level of criterion performance) led to significantly improved performance with respect to a relatively simple surgical procedure on human patients (laparoscopic cholecystectomy) [375].

- Chaudhry *et al* have shown that the initial familiarisation curve using MIST requires up to 4 repetitions and that *construct validity* still holds between basic surgical trainees and non-surgical subjects at 10 repetitions for most tasks [95]. The final level of performance at this point appeared to be asymptotic, but as far as the author is aware, no data beyond this region are available to confirm this.

- Grantcharov *et al* analysed the 'familiarisation curves' of three groups (experts, novices and intermediates) in ten trials over a period of one month [187]. Significant differences between the groups were observed on the first trial, but were not present in the last. As expected, experts showed little evidence of learning, whilst the performance of intermediates levelled at the fifth trial and the novices reached plateau at the seventh.

8.1.3 Training Research

In Chapter 3, the results of training research in clinical, military and industrial settings were examined. In these domains, *construct validity* test designs appeared to be unknown, the nearest logical equivalent being usability analyses, in which the opinions of a range of users are assessed[1]. Instead, researchers are generally much more interested in establishing transfer and retention properties of training programmes. The construction of learning curves for a number of surgical procedures suggests that after learning the basic techniques, a distributed training schedule of some 30–50 trials (or real cases) is effective for overcoming most errors. In addition, surgical volume would appear to be a factor in predicting surgical outcomes indicating that, after qualification, a deliberate practice schedule should be maintained.

To quantify training, flight simulation researchers have expended a good deal of effort in the hope of obtaining estimates for 'transfer'. But the current consensus is that accurate estimates for transfer are difficult and, more importantly, very expensive to obtain. Indeed, many 'transfer-of-training' measures exist but most should be considered meaningless unless the reliability of the test results has also

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[1] This contrast highlights a disturbing a trend in the surgical simulation literature which is that the opinions of participants, however skilled, are rarely published.

been established. On the other hand, there is some agreement in the literature that 'quasi-transfer' studies are effective. The main benefit of this approach is its simplicity (cf. Section 3.4.3.3):-

- Treatment and control groups are trained either exclusively with or without a particular feature of the simulator to a preset criterion level;
- In the same simulator, with the feature under test either enabled or disabled, the groups are then re-tested, perhaps under a variety of conditions.

Section 3.5 introduced a number of principles from psychomotor research studies which have become established over the past few decades. Failure to appreciate this work seems to have wrong-footed a number of evaluations, such as that of Prystowsky *et al* [321] (Section 2.3.5). In that study, the authors conjectured that *Schema theory*, developed by Schmidt in 1975 [361], was a sufficiently sound basis for supposing that 12 minutes' training on the VR device would produce a significant increase in performance on a catheter insertion simulation. In Schmidt's theory, however, *schema* are motor programmes which are developed over many deliberately varied practice sessions to allow planning for related movements. Practising throwing tasks at distances of 5m and 10m, for example, should generate good results when test throws are requested at, say, 8m. Research which has accumulated since that time has indicated that other factors may also be present, but has not contradicted the basic premise that practice variability is fundamentally important in the development of motor programmes [267, 362].

A related principle, which also seems to have been frequently overlooked, is that of practice scheduling ie. blocked versus distributed training. Whilst some evidence exists that blocked (repetitious) training may be valuable for young or inexperienced subjects, it should be avoided as a general rule. In particular, it seems that training by repeating set exercises tends to give good results during practice, but when transferred to the target environment performance is often very poor. Instead, training schedules should deliberately mix dissimilar tasks over many sessions so that subjects are forced to forget previous strategies in order that they have to be reconstructed later. An important corollary is that instantaneous results (over one session) are by definition, unreliable. Repeated tests must be performed, preferably over several days, to gauge performance: consistency and persistency are seen as the main markers of progress in the acquisition of skills.

A third principle, which simulator designers have tended to treat as arbitrary, is that of feedback schedules. *Intrinsic* feedback, ie. that which is purely a function of the task such as visual and force-feedback, must be presented appropriately in real-time (cf. results with SKAT, Section 2.3.4). On the other hand, *extrinsic* feedback (eg. error scores) has been shown to generate very different responses — too much score-related feedback tends to lead to charges of over-critical systems. On balance, the evidence suggests that trainees prefer feedback after successful trials so that they can adjust or build their own error-correction capabilities. Similarly, *augmented* feedback (additional 'virtual' feedback, such as the BDI 3D guide vector, see 2.4.3.3) may also be counter-productive. The evidence indicates that it tends towards 'crutch-like' dependencies, with high levels of performance in practice but poor performance in testing (ie. when the 'crutch' is removed) even compared to conventionally trained subjects.

8.1.4 Modelling, design and feedback

Vascular suturing presents several major challenges both to the surgeon and to simulation (surface wounds, by their nature, would allow considerably more latitude). The sutures must be placed to a precision of a few millimetres and the resulting wound closed to a very smooth contour, so that patency results — without causing further obstruction to the lumen of the vessel. The manipulation of the needle, tissues, patches, thread etc. requires two hands working asymmetrically, the only proviso being that occasionally the surgeon has to swap hands where access would otherwise be far too awkward. An immediate simplification made here, using a part-task approach, is that only one object was modelled — although we have assumed a second object (patch, tissue etc.) may exist or may be added later.

In allowing both hands to manipulate the mesh/tissue, it was preferred that deformation solutions should be combined rather than assembled and solved in one step. The main reason for this was that manipulation of the 'tissue' by the supporting hand would indicate that the collision detection model needs to be updated. If deformation solutions are separated, then those due to the needle can then be superimposed on that previously obtained to update the collision detection model and, crucially, forces can be kept consistent. FEM was seen as the model of choice here due to its greater accuracy (than mass-spring models), suggesting better fidelity and stability with multiple, superimposed boundary conditions.

The separation of deformation solutions also indicated that the system may benefit from parallelisation. Borrowing from Guiard's principle of asymmetric working, a design was put forward which proposed that work with the dominant hand should generate updates at *c.*1000 Hz for haptic rendering whilst work with the supporting hand would only require updates at *c.*30 Hz for graphics and collision detection. It was also supposed that whilst force-feedback could be related to the dominant hand via a haptic device, a simpler joystick type interface may be acceptable for use with the other hand, allowing more immediate control of needle angles, stereo settings etc. than, say, requiring the user to turn to the keyboard or mouse.

Following principles derived from psychology and aviation research (8.1.3 and Chapter 3), errors were indicated by graphical feedback when requested by the user on clicking the mouse pointer. The errors relayed were selected on the basis of those most likely to induce stress in the tissue: a real-time or delayed representation of stress would have been possible (based on FEM), but was not thought likely to have been helpful. This form of delayed graphical feedback was intended to promote learning rather than focus purely upon skills assessment.

Chapter 6 gave a full description of elastic solid mechanics using FEM. The method of *super-condensation* was then developed to allow the pre-computation of multi-point contact models necessary for bimanual working and real-time force display. The choice of parameters to define the tissue model were discussed and a volume test introduced to qualify this model. An extension to approximate more realistic tissue behaviour, the bi-phase model, was also described.

8.1.5 Evaluation

A series of pilot studies were undertaken to evaluate the *FESTIVALS* system which comprised: a learning curve and retention test, a transfer test to real tool use and a usability study. Of these, the transfer test proved to be the least successful, in the sense that no significant results were generated. It was nevertheless possible to use the results to give an estimate of the power of the test which may be of interest if future trials of this kind are undertaken. The other tests suggested that the simulator possessed several strengths and weaknesses:

- Bimanual working was permitted albeit many test respondents found the interface heavy to manipulate, and against this, the haptic display felt weak, though some people reported that this feeling improved during the session. Although realistic tissue parameters were used, the setting of a modest response was a deliberate policy to avoid excessive, unnerving responses and to prevent overheating the haptic motors. For the *Desktop* PHANToM model used here, overheating requires that the motors be allowed to cool for an hour or so.

- Significant improvement in error scores was observed after six sessions and was retained for many weeks. The method of delayed feedback was easy to comprehend and was not found to be intrusive, where scoring systems might have been demotivational or encouraged speed over technique. Many clinicians nevertheless felt that a method of scoring was needed, both for assessment and to encourage appropriate usage of the system.
- The system did not violate the concept of construct validity, and discrimination was positive for some efficiency characteristics during insertion of the needle.

8.2 Towards a model for learning

8.2.1 Limitations of the *construct validity* test

Tests between experts and novices have become commonplace in surgical simulation research although significant differences are usually only apparent when the test is based on efficiency parameters, such as time taken or distance moved [47, 48, 125, 126]. It is implicitly assumed that technical errors will cause delays or unnecessary movement and that measures of inefficiency will be inflated as a consequence. If this is not the case, perhaps because some illegal strategy is being employed, then the test may unaccountably fail. In vascular procedures, for example, the patient must always be kept in line of sight and hence minimal movement of the hand often requires a curved path. It follows that violations of this rule, if not detected by the simulator, may bias efficiency scores unfairly.

A further problem is that an optimal level of performance is always assumed to be paramount: the evidence here (although limited) suggests that a lower level of performance with the non-dominant hand may be preferable in situations where manoeuvring around obstructions with the dominant hand may be too slow or hampered. In such circumstances, it would be of considerably greater value to see how trainees cope with unusual circumstances, ie. how skills are transferred, rather than their best time in practice. Performance may also be depressed during training, an effect which was seen here and has been reported by numerous other researchers eg. Rosen *et al* [344] (2.3.4).

The fidelity of simulations is another issue which distinguishes assessment-oriented approaches from training approaches. In the assessment approach, significant discrimination of experts from novices is taken to be *prima facie* evidence of the value of the bench model or VR test. From the various studies of this kind, however, it has been consistently shown that individual differences tend to converge rapidly with practice (3.5.3) and even short periods of rehearsal can remove significant differences [48]. In these cases, therefore, it is difficult to know if the fidelity of the model has contributed to the success or failure of the test, especially if users' opinions are not reported. In fact, it seems necessary always to ask how much practice or experience would remove significant differences or, more simply, 'how reliable is the test?'.

This basis of construct validity testing was explored and challenged in Sections 3.3.2 and 3.6.2, where it was argued that this loss of reliability should be a major cause for concern. Significant differences are frequently observed between experts and novices, giving some level of support for the central construct that simulators can measure surgical skill. But, as noted above (and see 8.3.3), the usefulness of such tests for assessing trainees of intermediate status is in doubt. Given the premise that a consistent framework of theory is needed around such constructs [88, 304], this lack of resolution indicates that a period of reflection and reconstruction is now long overdue. A clearer model of learning is now vital. In their ski simulation study, Nourrit *et al* suggested that trainees learn by alternating between rival strategies (Section 3.5.9.2) and this interpretation would certainly be supported by the data generated here. In such circumstances, longer periods of training and retention testing are crucial if reliability is to be established.

In training-oriented studies, skills training, even with low fidelity simulators, has been shown to produce significant improvements over conventional classroom instruction [189, 353] and other researchers have found that departures from the highest levels of fidelity can actually enhance transfer [332, 414]. For simulator developers, this is usually a much more meaningful result. We are tempted to ask: 'what features of these training models might be important, and what aspects of training were missed?'. To respond to this question, the training-oriented groups may also have an answer — using *backwards quasi-transfer* (3.4.3.2).

8.2.2 Null hypothesis significance testing

The application of *construct validity* tests without regard for other forms of analyses appears to be symptomatic of null hypothesis significance testing (NHST) in general. Without other checks, it is often difficult to interpret NHSTs and critics of the method have often been scathing: 'significance testing retards the growth of scientific knowledge; it never makes a positive contribution' (Schmidt & Hunter 1997, quoted in Nickerson [297]). The psychology literature in particular shows a greater awareness of controversy about NHST. One of the main areas of confusion is in the conditional nature of the probabilities involved, such as the nature of Type I and II errors (some definitions are given in Appendix A.5). Another grey area is the difference between statistical and practical significance[2].

With this warning in mind, how should *construct validity* tests be interpreted? If the performance of experts and novices has been shown to be significantly different, this is of interest to the developers since it *indicates* (but does not prove) that the VR task gives an approximation to the real procedure. Importantly however, this result may be of little interest to clinicians since, as Reznick commented on the BDI simulator (2.4.3.3):

> The two groups are very disparate in terms of their surgical capabilities. It may be that simple explanations, like the ability to handle the needle holder or understanding the concept of pronation or supination in placing a needle, are as operative as the more complex abilities of performing the complete task of suturing [336].

In short, too much reliance has been placed upon the success or failure of *construct validity* tests and insufficient attention paid to the way that skills are acquired. One consequence is that little progress (if any) has been made in incorporating these systems into surgical training programmes. This situation is similar to that in aviation research over a decade ago (see 3.2.2) and indicates that despite the ingenuity of developers, the potential of VR to enhance learning in surgical techniques is still poorly understood.

8.2.3 Aspects of technique

Defining technique and measuring specific sources of error is not trivial. In the evaluation results of Test B, for example, the asymmetry of the pattern of sutures was due to a mixture of instrument handling, approach angles, depth of insertion etc. and it was not possible to quantify these adequately from the surface data (7.5.3). Similarly, efficiency metrics combine errors from many different sources, which are equally impossible to resolve.

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[2] Consider a hypothetical dart-throwing experiment in which the treatment group is blindfolded: the results may be highly significant statistically, but of no practical interest.

Since approach angles etc. can be easily sampled at high frequencies in VR devices, this section gives a *post-hoc* examination of the evaluation data to look at other potential error metrics and relationships. Attention here is focused upon angular changes during the insertion phase of each attempted suture as this was thought to be one of the most likely to cause tissue distress, especially if large or sudden movements could be detected. Figure 8.1 gives a visual display of accumulated twisting of the needle over this cycle. This quantity is related to *Plane angular error* (see 7.2.4). Here, however, the angular difference between each plane normal sampled (at *c*.33 Hz) is accumulated. Note that feedback during practice only gave graphical output of the average plane, and hence no information was provided to participants on this metric.

In the plot of Figure 8.1, only the results from a defined section of time are given, using sutures from the last session of surgical participants of Test C. The plot is intended to be read from top left to bottom right across the page in increasing order of experience: SHOs (Senior House Officers), SpRs (registrars) and CS (consultant surgeons). It can be seen the strokes formed tend to follow a similar slope which appears to be systematic error due to vibration modes of the hand and the equipment (namely the PHANToM). Deviation from this average slope suggests a significant contribution from human movement.

As a check of *construct validity*, it may be observed that the plot indicates that movements become more controlled and reduced in higher grades of expertise with less frequent sharp jumps (some of which are presumably a result of difficulty in handling the interface). The height of each stroke — ie. the total accumulated twist — is also reduced and this factor is significantly different between the SHO and SpR, and the SHO and CS groups at the $p < 0.01$ level. As a further check, it is interesting to note that this quantity was also observed to improve across the Test A practice trials during both the insertion ($F = 2.169$, $p < 0.001$) and retrieval phases ($F = 4.229$, $p < 0.001$).

It was anticipated that significant jumps (‘steps’ in the plot) would be more likely to occur at the end of each stroke ie. due to the release of the locking mechanism, but this does not seem to be the case. In fact, movements across this region are remarkably smooth and this would seem to be especially true for the registrar working with the non-dominant hand — the chief impact of which is in the height of the stroke. The latter seems to reflect increased efficiency of the insertion phase by consultants (see 7.4.4.2 and Figure 7.22). It should noted, however, that there were no significant differences between these groups for overall time per stitch or

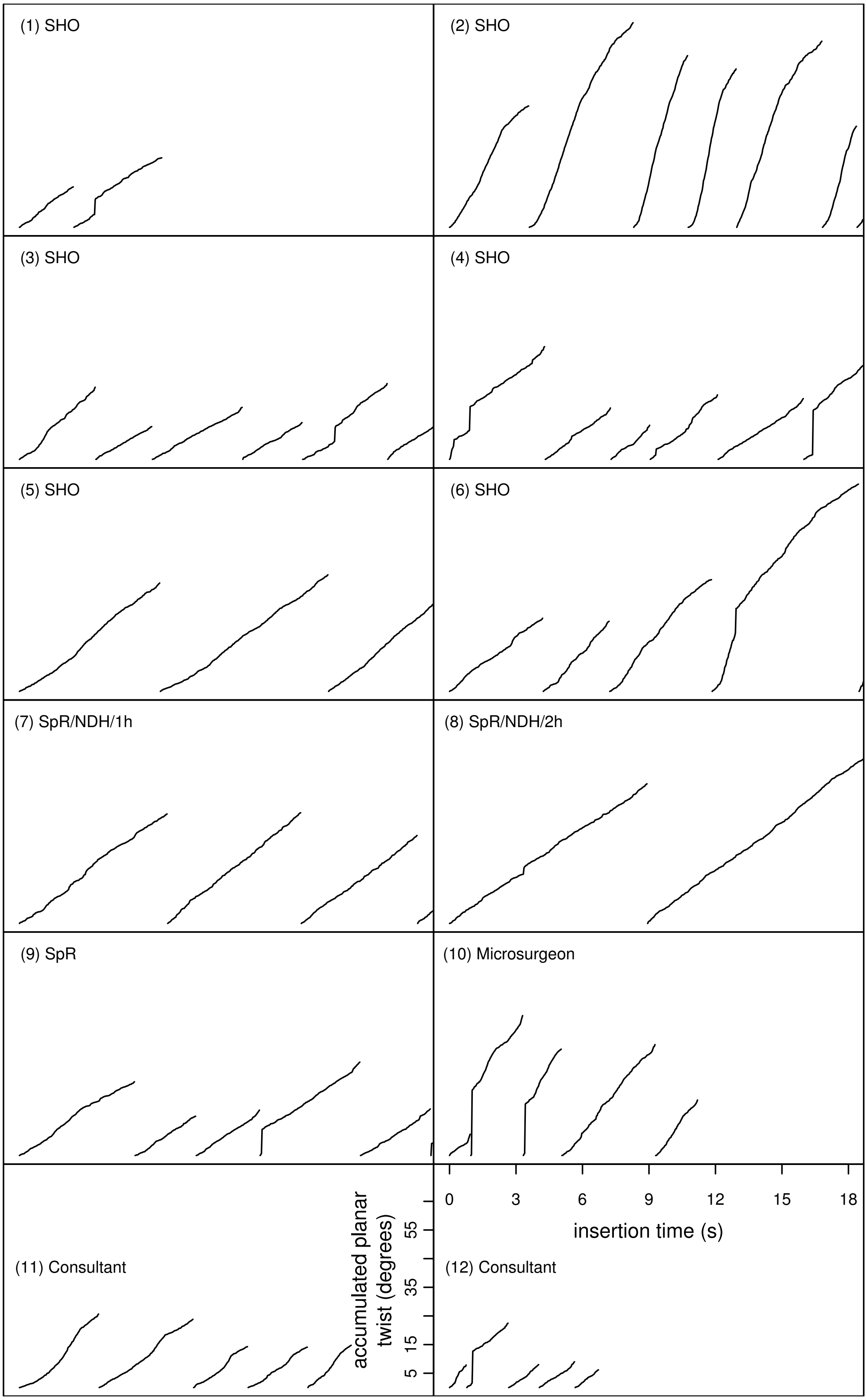


Figure 8.1: Cumulative planar twisting errors

inter-stitch time (even with the NDH condition) and hence the total planar twist quantity would seem to be much more closely related to specific technical expertise.

8.2.4 Error correction

The use of more visual data displays in the above, rather than overall test statistics, is thought to be a valuable contribution since it gives a clearer understanding of the nature of the data and may be able to provide more useful feedback to trainees. Since the system defines discrete phases for the components of each suture (5.2.2.3), it is possible to correlate different error quantities in the same display. The resulting profiles must be interpreted with care, however, as the parameters are usually measured with respect different reference criteria. The striking angle was an obvious choice for investigation here because it already has an obvious reference to the normal of the intersected triangle and the data showed a large range of variation.

Twisting of the needle during the insertion phase was suspected to be closely linked with elevating stress levels in tissue. To investigate the relationship with the strike error, therefore, a further error term, *precession error*, was defined as the angle between the normal of the needle plane and the average normal of the phase. This definition is intended to convey that the error describes an angle of precession ie. that the needle was being twisted about a relatively stable axis of rotation. This interpretation is partly based upon the appearance of the data and is discussed further below.

Figure 8.2 plots the precession error against strike error for a small number of adjacent test sutures obtained from surgical trainees, registrars and consultants in Test C. (Appendix E contains additional plots of these error profiles from all the surgical trainees, registrars and consultants in Test C, see Figures E.1 and E.2.) The aim of these plots is to present a visual record in the manner recommended by Tufte [426, 427], so that patterns in the data can be examined by eye. There are several key points to make in general: firstly, the plots show a progression from less experienced SHOs at top-left, to consultants at bottom-right; and secondly, complete trials are shown, so that adjacent suture attempts are adjacent in the figure.

It should be emphasised that any conclusions drawn must be tentative, given the limited size of the data set and some level of variation in the clinicians' choice of approach. In general, however, the consultants' movements appear to be defined by a smaller number of features, which occur more often in parallel. Also, the consultants appear to be more much more likely to repeat this strategy from one 'stitch' to the

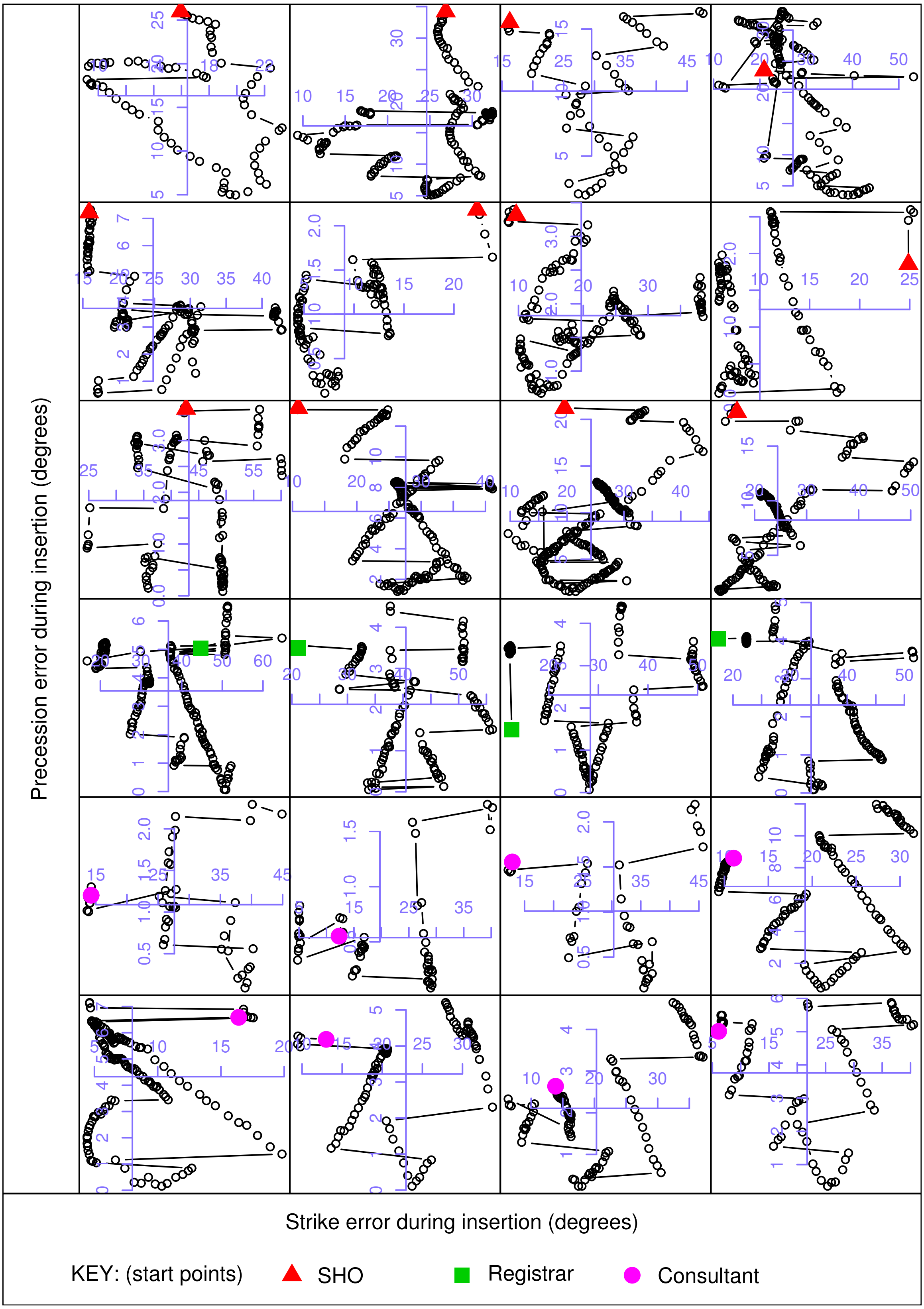


Figure 8.2: Selected precession error profiles

(NB. Scales vary, axes are drawn through the centroid of each profile) next with their movements kept within the same error region (Figure E.2). The trainee data, on the other hand, shows much greater variation with more frequent and larger 'jumps', indicating large potential stresses. It is argued, therefore, that the plots suggest a greater level of organisation in the movement actions of experts, since there is a more deliberate rhythm in which a motor strategy has been planned or selected before being executed.

In brief, the experts' data appears to be less convoluted: the occurrence of parallel, perpendicular and even, sometimes, horizontal and vertical paths would seem to indicate that errors are being corrected in a much more deliberate pattern. That one angle seems to be held constant, whilst the other is adjusted, is the reason behind the use of the term *precession* here: the implication is that experts are using a few stable axes of rotation and applying corrections by making adjustments along each in turn. Novices on the other hand, are less able to control these adjustments, and the axes of rotation seem to vary. This interpretation, albeit tentative, is in good agreement with Adams' definition of skill as the ability 'to bring about some end result with maximum certainty and minimum outlay of energy' (3.5.1).

These plots are offered as a potential basis for future research as time does not permit more complex statistical analysis here. It is possible, however, to look for corroboration in these inferences using the learning curve data. In Figures E.3 and E.4, there is a marked tendency towards large horizontal jumps during the earlier phases, which diminishes a little over time, but suggests better control of precession error than strike error especially in the beginning. Interestingly, however, the plot pattern seems most organised during the retention phase, with the recurrence of a diagonal 'cross' shape. If this is genuine, it suggests that the weeks between practice and retention tests were important for reorganisation of motor behaviour. It is also fascinating to note that this pattern seems to be echoed by earlier 'cross' patterns during the more chaotic central phase of training ('phase II'), suggesting that this new action plan for error-correction was incipient at that time.

8.3 Future work

8.3.1 Limits of performance

To gauge possible areas of improvement and to provide an estimate of the training limits of the system, Table 8.1 gives the best median values obtained for various error metrics in Tests A and C (median values are thought to be a better estimate of the central value given the limited nature of the Test C data). A number of features are of note:

1. The Test A data shows a general improvement (but note that this data does not describe the more erratic central phase) such that plane, strike and edge direction errors are poorly distinguished between the last Test A trial, the SHO and CS groups (these differences were non-significant though perhaps with more data, these may have become so);

2. For the time taken for each suture (total and the inter-stitch time), the table shows large difference between the last Test A trial and the SHO and CS groups, with the former taking *c.*50% longer to complete each suture; the CS and SHO groups, however, are indistinguishable;

3. The performance of consultants *is* distinguished (and is generally significantly different) from the other groups in the time taken and total displacement during the insertion and retrieval phases, sometimes by a factor of 2 or more.

The last point might seem to indicate that the consultants' performance has merely become more efficient with time, following some 'practice law'. From the first 2 points, however, it is clear that this faster performance has not resulted in greater levels of error or faster overall performance. This suggests that the experts may be preparing more carefully so that greater performance is obtained during the more critical insertion and retrieval movements ie. that there is much stronger element of technique involved. This view is supported by the evidence for greater error control during these phases described above (8.2.4). Otherwise, some kind 'speed-accuracy trade-off' — in the manner of Fitts' Law (3.5.5.2) — would be expected.

8.3.2 The physical interface

The favourable comparison between that obtained during the last trial in Test A and the consultants' performance and in Table 8.1 indicates that the system may be adequate to provide some level of training and assessment. Plane errors of *c.*10° and edge direction or strike errors of *c.*15° seem apparently reasonable. It is likely, however, that it is the system itself which is imposing these limits and many users reported having some difficulty with the interface. This section briefly outlines some possible adaptations for improvement.

	Phase	Test A practice trials		NDH trials		SHO	CS
		first	last	1-handed	2-handed		
Plane angle (°)	—	36.9	7.0	5.0	2.2	7.6	11.7
Edge direction (°)	insertion	32.0	16.5	14.2	19.7	15.6	17.8
	retrieval	17.9	16.1	11.8	20.0	19.3	22.7
Strike angle (°)	insertion	16.8	14.1	31.0	29.4	18.4	14.6
	retrieval	20.9	13.2	27.2	48.7	19.2	20.5
Movement about centre (mm)	insertion	1.2	0.7	1.6	1.5	1.3	1.2
	retrieval	0.9	0.9	1.3	0.8	1.4	1.3
Distance between centres (mm)	—	2.8	1.5	1.3	1.8	2.7	3.4
Principal component (°)	insertion	48.6	12.0	40.2	11.4	34.6	35.7
	retrieval	26.6	23.9	33.5	29.3	36.9	36.9
Total displacement (mm)	insertion	25.9	17.4	22.8	41.8	23.2	12.8
	retrieval	21.6	15.9	27.8	5.3	14.5	14.6
Time taken (s)	insertion	7.1	5.1	5.2	9.8	2.8	1.2
	retrieval	5.7	4.7	5.9	1.1	1.4	1.3
	interstitch	17.1	13.7	7.5	19.4	10.9	11.9
	total	36.7	30.8	24.4	42.5	19.6	21.8
Test C data: NDH (Registrar), SHO=Senior House Officer, CS=Consultant surgeon							

Table 8.1: Performance table of median scores

Stereo and depth cueing:

There are several physical reasons for the loss of depth cueing in VR systems. Where stereo graphics are displayed, one of the main omissions may be the lack of shadows. In graphical displays, shadows are reasonably straightforward to achieve against a flat surface, since a single matrix transformation can be used, depending on the position of the shadowed light source. In more complicated environments such as this (with curved surfaces) shadows are more difficult to realise, especially in real-time. It may be possible, however, to provide some kind of approximation which improves upon the situation here, in which shadows were overlooked entirely: a crosshair was displayed in an attempt to mediate this problem (see 5.3.3).

A further problem in the use of the public domain version of Open Inventor is the use of parallel, symmetric viewing frustums — the so-called 'twisted eyeball' problem [218], since human eyes tend to be directed 'inwards' towards the point of main focus. The commercial version of Open Inventor supports fully asymmetric viewing frustum cameras, which claims to improve depth perception though this has not been tested here [4].

Posture:

It has been noted that the use of a semi-reflective mirror allows better posture (5.3.3) in that a standing position is permitted where the forearms can work perpendicularly to the body. It should be noted, however, that this may not be entirely adequate. The BDI system (Figure 2.12), for example, allowed a standing position, but did not provide a resting place to steady the forearms. This appears to be essential in some aspects of surgery and perhaps especially so for vascular work. For the evaluations undertaken here, it was apparent that asymmetric bimanual working was the normal mode of operation, but not necessarily using separate tools: the more experienced surgeons nearly all used one hand to support and steady the other by resting on the table.

The evaluation summary in Table 8.1 indicates that using hands separately had a profound effect upon the nature of errors, plane errors being reduced, for example, whilst strike angle errors increased. More work is required to validate the usefulness of this effect, but from a motor psychology perspective, such variations are certainly desirable. It may also be observed that most people found the functionality of the Spacemouse sufficient for setting the needle and that a second haptic device might not have improved this capability, given the problems of depth cueing described above.

Forces:

Many of the test participants found the interface heavy to use, with some soreness resulting after an hour. This is thought to be partly a result of the PHANToM interface and a solution will probably come from better engineering. The new *Omni* devices from SensAble [373], for example, would seem to allow better adaption to hand tools. The use of a reed switch here also added extra weight (since a magnet was also needed) and a simple electrical contact may be more desirable. It seems reasonable to think that these problems may be easily addressed in future. If so, it should be straightforward to find more appropriate settings for the FEM and biphase model by testing a range of models, perhaps in a quasi-transfer setting (see 8.3.3 below).

A more difficult problem was the issue of determining the threshold of force/stress for needle puncture. The component of velocity directed towards the mesh was used here and although some users found this adequate, many did not. A more appropriate test might make use of the FEM stress tensor, though this would require more extensive testing than time has permitted here. A related problem was that the bimanual condition showed some tendency towards instability especially when moving the needle close to the velocity-puncture parameter. The Linux GHOST driver was also prone to crashing near these critical regions and hopefully this situation will improve in future releases.

Some users reported that torque resistance to passing the needle through the tissue would be desirable, but this would certainly require a more complex haptic feedback device. At the time of writing, some PHANToM devices support torque feedback, but are heavier still than the *Desktop* model. The appropriate use of torque is still an ongoing subject of research [161, 200, 337].

Collision detection:

The stability of the system would probably be measurably improved by the implementation of a more sophisticated method of triangle selection based, perhaps, on graphics hardware (4.6.3).

8.3.3 Supporting training and transfer

In Section 8.1, it was noted that research in support of training schedules was still much needed and that the failure to appreciate similar work in motor psychology had contributed to the poor findings of a number of simulator studies. This section gives some brief recommendations for future research with regard to this issue.

In the first place, it should be noted that efforts to relate skills solely to dexterity or visuo-spatial abilities, ie. by using 'selection-oriented' tests for aptitude (3.1.1), have largely been fruitless. Some researchers have rejected this idea outright, pointing out that deliberate practice is necessary whatever innate abilities might be possessed [148]. In any case, practice and training effects must be considered during tests, as simulators often have better training characteristics than assessment properties (2.4.4.3). Training research (clinical, military etc.) has led to important new methods for assessment and, where training has been considered more fully, has produced good results in surgical simulator studies (eg. [375]). One area in which *quasi-transfer* studies might be able to assist is in determining appropriate levels of scoring and feedback ('Knowledge of Results'). In particular, it would be very useful to establish: (i) whether the delayed feedback schedule presented here could be improved, and (ii) whether particular scoring systems would motivate or demotivate trainees.

Secondly, progress should not be considered as a simple function of practice. In the review by Pinkerton and Peterson, the authors point out that even at best, surgeons get worse before getting better when learning a new technique [317]. Moreover, the learning environment, communication and teamwork can also play a vital role in preventing or promoting learning [63, 172]. New models to describe these learning processes are urgently needed to allow stronger methods of statistical assessment than are currently available (8.2).

Motor psychology research suggests that practice should be varied; it is more effective if both hands are used and there is an interchange between the roles of the dominant and non-dominant hand; it should be distributed over a reasonable time period so that forgetting and remembering processes are reinforced. In the domain of vascular surgery, it might be anticipated that early training should begin with basic forehand technique, but, perhaps after a few sessions, subjects should be persuaded to practise more difficult overhand and backhand techniques. As technique grows more consistent, perhaps up to preset criteria, new tissue models and needle types should be introduced. Retention and transfer tests would also then be appropriate and at some point, it would probably be necessary to identify remedial or additional training to bridge the gap between virtual and real world procedures.

To achieve these aims, our experience here suggests it may be necessary to recruit trainees or to integrate simulator training and assessment into their curriculum. Voluntary testing is not sufficient since trainees are unwilling to commit the necessary time — and time is needed to allow skills to develop and be tested.

Chapter 9

Conclusion

> 'Connell said once that he knew he was finished with a short story when he found himself going through it and taking out commas and then going back through the story again and putting commas back in the same places. I like that way of working... That's all we have, finally, the words, and they had better be the right ones, with the punctuation in the right places'
>
> - Raymond Carver, *On Writing*, in Fires (1981)

Today's health professionals are facing a crisis in training needs: on one hand, the working hours of junior doctors and experience at the operating table are being reduced; on the other, patients are growing ever more critical and litigious. VR systems may provide a solution, but whilst hardware costs have fallen in recent years, they are still expensive when compared to conventional training methods and hence clinicians have been reluctant to adopt them. The challenge for researchers has therefore been to create realistic — but affordable — surgical interfaces and to provide convincing assessments.

This thesis has investigated the methods by which VR tools may be able to contribute towards training solutions. VR systems possess many potential advantages:

- Tests may be standardized with respect to treatment and environmental variations, and hence are more powerful;

- Experts may give feedback to allow prototypes to develop quickly (this is not possible with most *in vitro* systems);
- Models and tasks can increase in complexity, towards higher levels of assessment such as decision-making;
- Training on the same model can continue indefinitely and under the same assessment conditions, with the potential for ‘overtraining’;
- Virtual tools can be accurately tracked, so that sources of error at critical phases can be examined or replayed;
- ‘Above real-time training’ conditions can also accommodated, using ‘compressed time’, or perhaps more appropriately for surgery, ‘compressed space’ scenarios.

Other areas of research have been found to contribute to this debate. Clinical research, for example, suggests that the learning curve for many procedures is ‘negatively accelerated’ ie. it is steep initially but after a finite number of attempts, the performance is usually indistinguishable from that of experts (except that trainees are usually still much slower). For simulator research, however, it is particularly significant that surgical errors are common during the early period of growth and that error rates are higher where skills are not being maintained and ‘surgical volume’ is low (3.1.4).

These findings strongly suggest that the most powerful roles that simulators may be able to play are in the initial training of particular techniques (say, through the first fifty trials) and in maintaining those skills once acquired. In particular, surgical simulators should allow trainees to be tested in an environment of modest stress while the technique is still being mastered, rather than having to perfect their technique on real patients. Ultimately, however, it seems that trainees must be assessed on real patients, with the additional psychological stresses that this must involve (perhaps under some kind of proctoring scheme; see Section 2.1.2).

A thorough search of the surgical simulation literature suggested that the findings of training researchers had often been ignored by developers of VR systems, and was a contributory factor in a number of poor evaluation results. Moreover, short-term studies to test *construct validity* often failed to consider the reliability of the results, so that the *predictive validity* of these systems is essentially zero (Equation 3.1, Section 3.3.1). Under these circumstances, it remains acutely difficult for new (and expensive) VR systems to be accepted by the medical community.

By contrast, principles established in motor psychology research over the past few decades often emphasised much more long term aims such as transfer of training, delayed feedback schedules and practice variability. Adopting these ideas, a design for a virtual suturing simulator was constructed which allowed considerable freedom for the user to set and manipulate the scene. In particular, the trainee is able to manipulate 'tissue' with either hand, to set the desired approach angle of the needle and to operate the needle driver locking mechanism to release and retrieve the needle. A straightforward graphical display of error feedback was also made available when specifically requested.

The FEM was adapted to build a powerful deformation model to support graphical and force rendering for bimanual working. This model was tested and extended to allow a more realistic force response. Evaluation of this system showed that the system possessed good training and retention characteristics. In addition, a usability study collected feedback from clinicians which showed a generally favourable response and allowed several recommendations for future development.

By considering discrete phases of the suturing data collected in these evaluations, it was possible to show that *construct validity* held for several metrics. This was of particular interest because it appeared to show that experts were much more capable of planning specific movements in advance so that, for example, insertion of the needle was typically very fast, but critically, other errors were not exaggerated as a result. In other words, expertise (and hence *construct validity*) was much more closely tied to specific methods of error-control than has hitherto been achieved. Furthermore, by plotting profiles of this error data, it appeared that experts tended to use a much more organised method of correcting movement errors. This finding led to a novel proposal for an error-correction model of expertise.

Appendices

Appendix A

Glossary

A.1 Validity

Face	“Experts review their tests to see if they seem appropriate on their face value”; eg. the chosen tasks resemble those that are performed during a surgical task
Construct	“The degree to which the test captures the hypothetical quality it was designed to measure”; eg. if the tasks were designed to test acquired skill, experts should perform better than students
Concurrent	“The relationship of the new test scores and those from evaluation in actual working conditions”; eg. the scores on the current test correspond to those on similar or *gold standard* tests
Content	“A detailed examination of the test is undertaken by experts to see if they are appropriate and situation specific”; eg. the tasks for measuring psychomotor skills are actually measuring those skills and not anatomical knowledge
Predictive	“Determining the extent to which the scores on a test are predictive of actual performance”; eg. those who do well in the test will do well in the operating room
Internal	The idea of internal validity is that the procedures have worked correctly and the measurement adequately represents what we want to measure. There are several threats: (a) subjects’ reactivity to treatment , (b) subjects’ reactivity to measurement, (c) biases in responses due to incorrect

	experimental procedure, (d) biases of recorders/observers, (e) failure of the treatment to 'take' and (f) intrusion of external factors (distractions, environmental conditions etc.) [250].
External	The extent to which the experiment is applicable to the outside world. One major concern is whether the treatment and its measurement represent what our theory is really describing. Another is whether controls of the experiment have removed crucial aspects of reality. Some limitation of this form of validity is usually permitted, given that most models are simplifications of the real world anyway [250].

Reliability

Inter-rater	Reliability of test scores observed by different raters.
Test-retest	Reliability of test scores measured at different points in time. Participants may remember and reject strategies for solving problems during retesting, suggesting that a better score is more likely. This field has explored extensively wrt children's IQ etc, where it is expected that differences of a few months can have a significant effect, see [228].
Coefficient	Reliability refers to the dependability or repeatability of test scores that distinguish between superior and inferior performances. Reliability coefficients range from 0.0, which indicates total inconsistency in the ability of scores to discriminate, to 1.00, which indicates total consistency [65].

A.2 Psychomotor skills

Feedback	*Intrinsic*: the visual impact or forces experienced by the user performing the task; eg. from the feel of the ball hitting the racket in tennis, a good player can tell if he has played a good shot. *Extrinsic*: feedback provided from outside the performer eg. by supervisor or umpire - usually indicated by a score
KR	*Knowledge of Results*: feedback presented as a score or an outcome to the user. The psychology literature, eg. [406], argues that KR provided during or immediately after the task will degrade performance - the user should be permitted to evaluate their own errors first

KP	*Knowledge of Performance*: Evaluation of the user in terms of their biomechanical action eg. the angle of the elbow in a tennis serve. Much less frequently evaluated than KR

A.3 Learning

Fitts and Posner's Phases

Cognitive	Perceptual cues have to be taught or explicitly learned, probably in a simplified version of the task
Associative	Responses that must be learned start to become readily available, old habits are erased and errors are gradually eliminated
Autonomous	Skills become automated, so that they require less cognitive control and are less prone to error

Rasmussen's Behaviour Model

Knowledge	The highest level of complexity is knowledge-based behaviour (KBB). It is controlled by the highest level of the processing hierarchy, relies upon a ”mental model” of the system in question, and in general terms is to be strongly avoided because what it achieves in terms of sophistication it loses in the time it takes. KBB is therefore what you have to turn to only when SBB or RBB are momentarily not up to the task at hand. As for the nature of the information at this level, KBB is described as relying on symbols. These are defined as ”abstract constructs related to and defined by a formal structure of relations and processes”.
Rule	The next level of complexity is rule-based behaviour (RBB). It is controlled by the middle level of the processing hierarchy, and may be characterised as consisting of ”a sequence of subroutines in a familiar work situation”. As for the nature of the information at this level, RBB is described as relying on signs to indicate the state of the environment. These are defined as ”related to certain features in the environment and the connected conditions for action”.
Skill	The simplest form of behaviour as skill-based behaviour (SBB). It is controlled from the lowest level of the cognitive processing hierarchy, and

may be characterised as ”smooth, automated, and highly integrated” and takes place (critically) ”without conscious attention or control”. As for the nature of the information at this level, SBB is described as relying on signals, which are defined as ”representing time-space variables from a dynamical spatial configuration in the environment”. [NB. Rasmussen explicitly warns that ”the boundaries between skill-based and rule-based performance is not quite distinct”.] [328, 388]

General

Implicit	Learning apparently acquired subconsciously through performing some task; eg. learning explicit rules for catching a ball has been found to degrade performance. Telegraphy studies, however, show that explicit teaching, when the rules are better understood can improve the rate of learning
Distributed	or Spaced (cf Massed) training undertaken over a long period with a significant inter-trial time
Blocked	(or Massed) training describes repeated training of a particular task. This method tends to produce good initial results, but poor retention and a low level of adaptability. Schmidt & Wrisberg [362] comment that ”The paradox of blocked-practice scheduling is that it produces effective performance during initial rehearsal but does not create lasting learning . . . people either fail to practice the target skill, or they practice the target skill in a context which is not the same as the target context.”
Random	To avoid the poor quality of blocked training, various authors have suggested that training should be randomly organized, so that if 3 tasks or sub-tasks need to be mastered, they should be practiced in random order [383]. The effect is then one of contextualised interference: since the performer has to keep recalling elements of each task, they are not so easily forgotten.

A.4 Task classification

Schmidt points out that there are a number of possible ways to classify psychomotor tasks, although none of these are exclusive, and many tasks involve a mixture of characteristics (which may change over time):

1. Discrete/Serial/Continuous: A discrete task is often of very short duration and is defined by a distinct beginning and endpoint, such as catching a ball. Serial tasks require a series of different movements (which may have to be learnt separately) to complete the task eg. changing gear in a car. Continuous tasks are often rhytmical or repetitive in nature, with an ongoing stream of actions such as swimming or steering a car.

2. Motor/Cognitive elements: Motor skills are primarily determined by the quality of the movement itself, when the objective imposes little or no mental load eg. jumping a hurdle. In cognitive skills, the emphasis is upon the mental difficulty since no particular skill is required to execute the movement, as in the game of chess.

3. Open/Closed: this viewpoint considers the way that the environment may change the nature of the task. In closed motor tasks (such as gymnastics, hitting a golf ball etc), the movement can be planned in advance assessing, if necessary, any possible environmental influence. In open tasks (ground strokes in tennis, white-water canoeing), the influence of the environment must be constantly re-evaluated, often with decisions needing to be made as quickly as possible.

A.5 Null hypothesis significance testing

p-value	The *p-value* obtained as the result of a null hypothesis significance test is the probability of making a Type I error given that the null hypothesis is true.

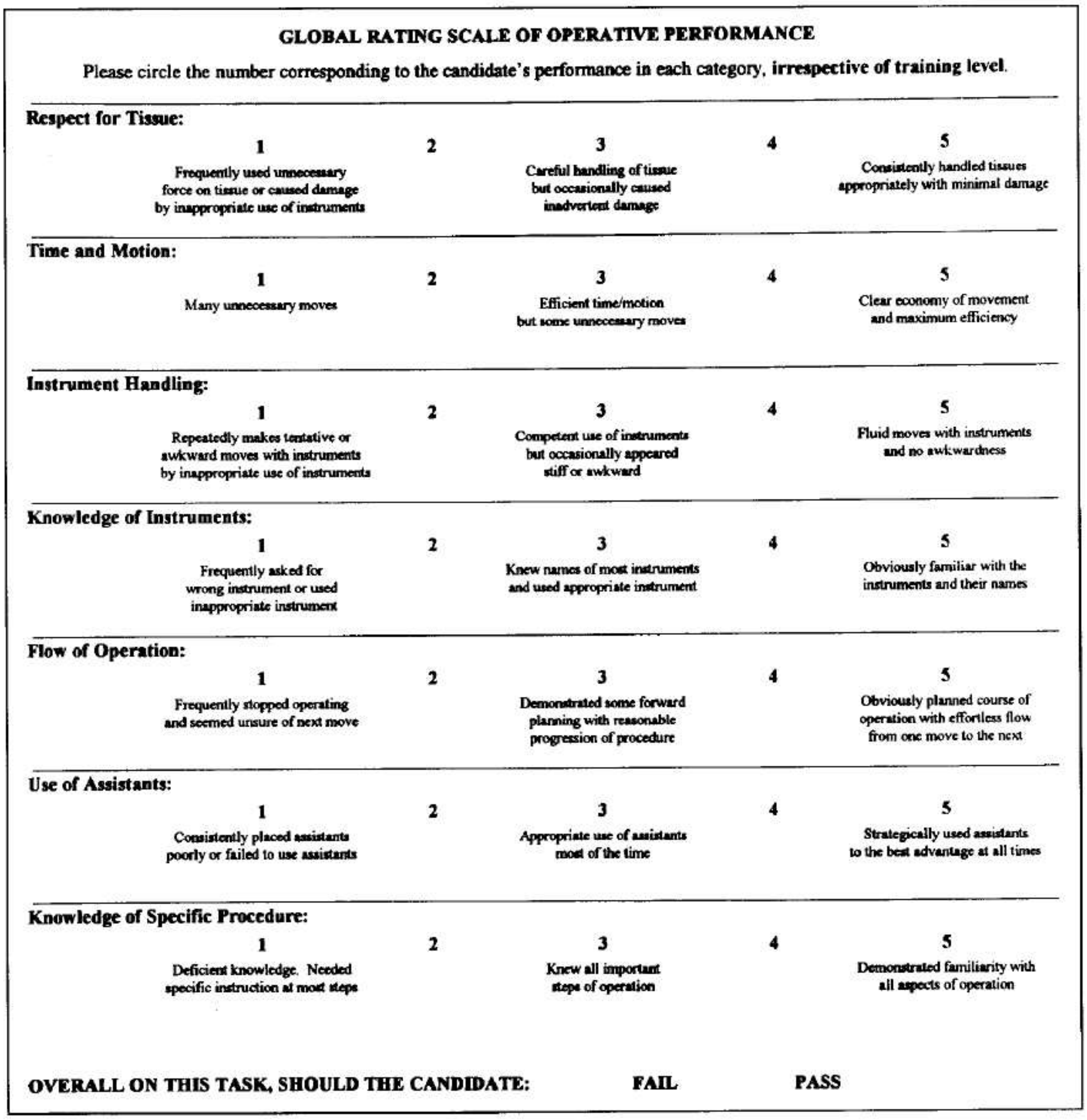
Errors:

Type I	Occurs if the null hypothesis is rejected, given that it is true.
Type II	Occurs if the null hypothesis is accepted, given that it is false.
α	Is the specified limit of acceptance for significance for Type I error, often set at 0.05.
β	Is the specified limit of acceptance for significance for Type II error, sometimes set (if at all) at 0.2.

Power	The probability of rejecting the null hypothesis, given that it is false. A statistical power (computed as $1 - \beta$) of 0.8 is usually quoted as being ideal.
Sphericity	An important assumption of many statistical procedures, is that a random factor which causes variation in one subject's measurement to be high (or low) at any point in time should not cause fixed effects in the next reading taken. In particular, learning effects usually violate the sphericity assumption. Failure to correct for violations of sphericity can lead to low p-values, and hence Type I error.

Appendix B

OSATS Checklist Examples



GLOBAL RATING SCALE OF OPERATIVE PERFORMANCE

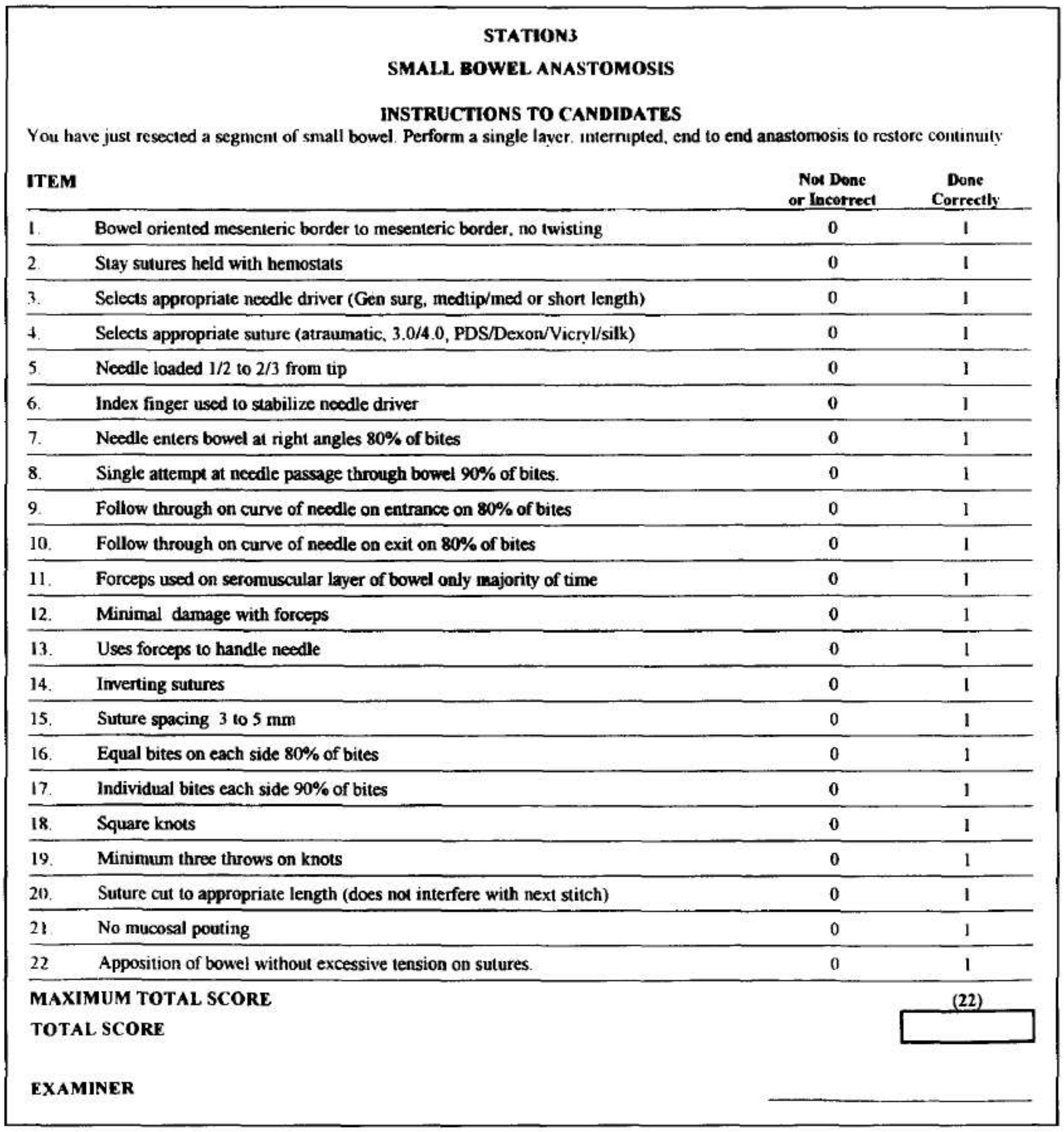
Please circle the number corresponding to the candidate's performance in each category, **irrespective of training level.**

	1	2	3	4	5
Respect for Tissue:	Frequently used unnecessary force on tissue or caused damage by inappropriate use of instruments		Careful handling of tissue but occasionally caused inadvertent damage		Consistently handled tissues appropriately with minimal damage
Time and Motion:	Many unnecessary moves		Efficient time/motion but some unnecessary moves		Clear economy of movement and maximum efficiency
Instrument Handling:	Repeatedly makes tentative or awkward moves with instruments by inappropriate use of instruments		Competent use of instruments but occasionally appeared stiff or awkward		Fluid moves with instruments and no awkwardness
Knowledge of Instruments:	Frequently asked for wrong instrument or used inappropriate instrument		Knew names of most instruments and used appropriate instrument		Obviously familiar with the instruments and their names
Flow of Operation:	Frequently stopped operating and seemed unsure of next move		Demonstrated some forward planning with reasonable progression of procedure		Obviously planned course of operation with effortless flow from one move to the next
Use of Assistants:	Consistently placed assistants poorly or failed to use assistants		Appropriate use of assistants most of the time		Strategically used assistants to the best advantage at all times
Knowledge of Specific Procedure:	Deficient knowledge. Needed specific instruction at most steps		Knew all important steps of operation		Demonstrated familiarity with all aspects of operation

OVERALL ON THIS TASK, SHOULD THE CANDIDATE: FAIL PASS

Figure B.1: OSATS global checklist

(from Reznick *et al* 1997 [335])



STATION3

SMALL BOWEL ANASTOMOSIS

INSTRUCTIONS TO CANDIDATES

You have just resected a segment of small bowel. **Perform a single layer**, interrupted, **end to end anastomosis** to restore continuity

ITEM		**Not Done or Incorrect**	**Done Correctly**
1.	Bowel oriented mesenteric border to mesenteric border, no twisting	0	1
2.	Stay sutures held with hemostats	0	1
3.	Selects appropriate needle driver (Gen surg, medtip/med or short length)	0	1
4.	Selects appropriate suture (atraumatic, 3.0/4.0, PDS/Dexon/Vicryl/silk)	0	1
5.	Needle loaded 1/2 to 2/3 from tip	0	1
6.	Index finger used to stabilize needle driver	0	1
7.	Needle enters bowel at right angles 80% of bites	0	1
8.	Single attempt at needle passage through bowel 90% of bites.	0	1
9.	Follow through on curve of needle on entrance on 80% of bites	0	1
10.	Follow through on curve of needle on exit on 80% of bites	0	1
11.	Forceps used on seromuscular layer of bowel only majority of time	0	1
12.	Minimal damage with forceps	0	1
13.	Uses forceps to handle needle	0	1
14.	Inverting sutures	0	1
15.	Suture spacing 3 to 5 mm	0	1
16.	Equal bites on each side 80% of bites	0	1
17.	Individual bites each side 90% of bites	0	1
18.	Square knots	0	1
19.	Minimum three throws on knots	0	1
20.	Suture cut to appropriate length (does not interfere with next stitch)	0	1
21	No mucosal pouting	0	1
22	Apposition of bowel without excessive tension on sutures.	0	1
MAXIMUM TOTAL SCORE			**(22)**
TOTAL SCORE			☐

EXAMINER ____________________

Figure B.2: OSATS task specific checklist (small bowel anastomosis)

(from Reznick *et al* 1997 [335])

Appendix C

Risk Assessment

Appendix D

Evaluation Questionnaire

Appendix E

Additional Figures

Note

The data displayed from Test C (Figures E.1 and E.2) comprises nearly all the ‘stitches’ obtained from the SHOs, registrars and consultant surgeons using their dominant hand (for presentation purposes, the first two ‘stitches’ were removed from the subject who contributed most data).

The data displayed from Test A (Figures E.3 and E.4) show all ‘stitches’ in every third trial, starting from the first trial and closing with the last trials of the practice and retention phases.

In the varied-scale plots, the scales have been automatically selected by software to match the extents of the data. Refer to the fixed scale plots to see the the actual region occupied by the data.

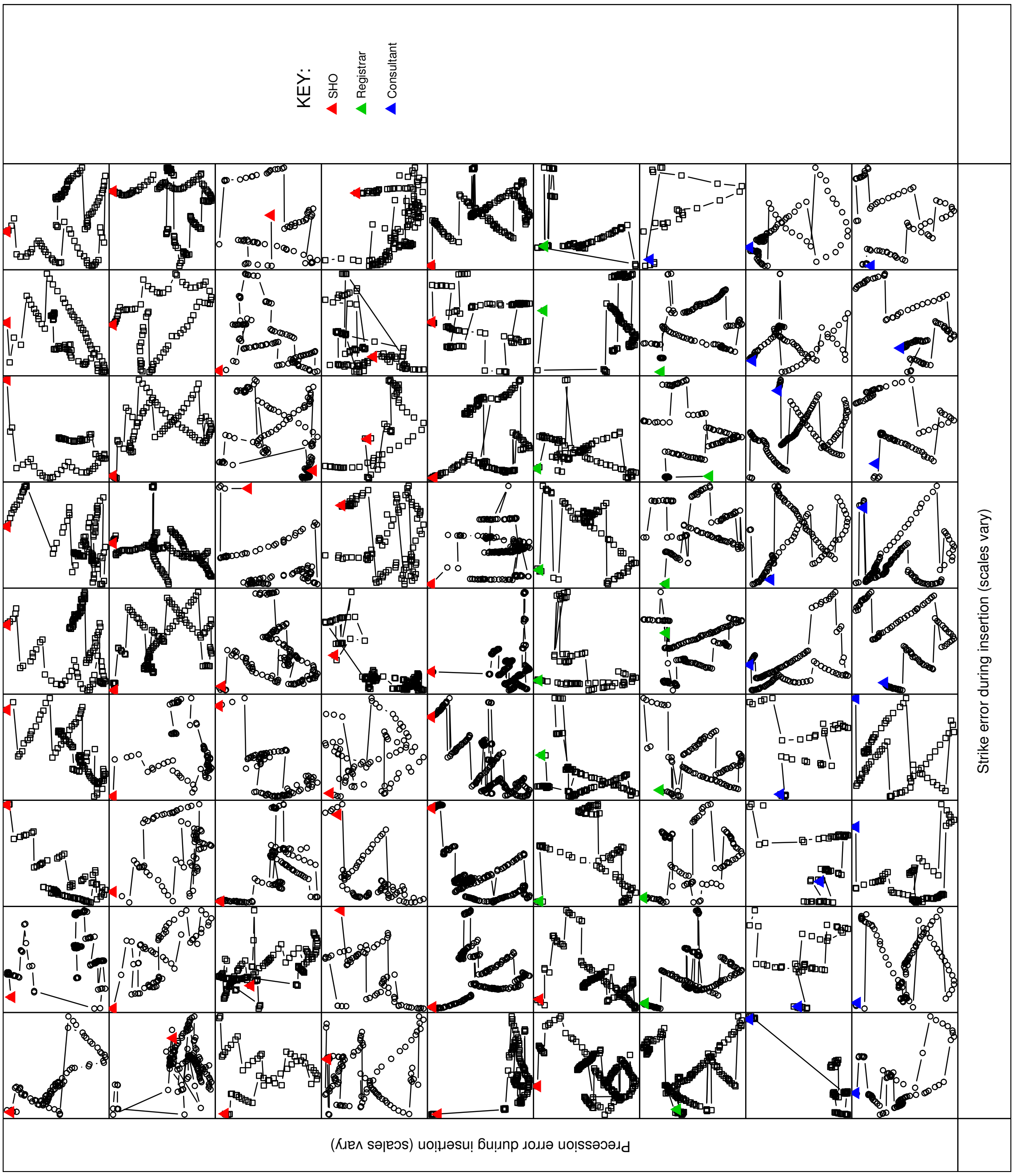


Figure E.1: Correlation between errors using Test C results at varied scales

(Note: alternate trials are indicated by circle and square symbols in the plots; coloured triangles indicate the start point of each sequence.)

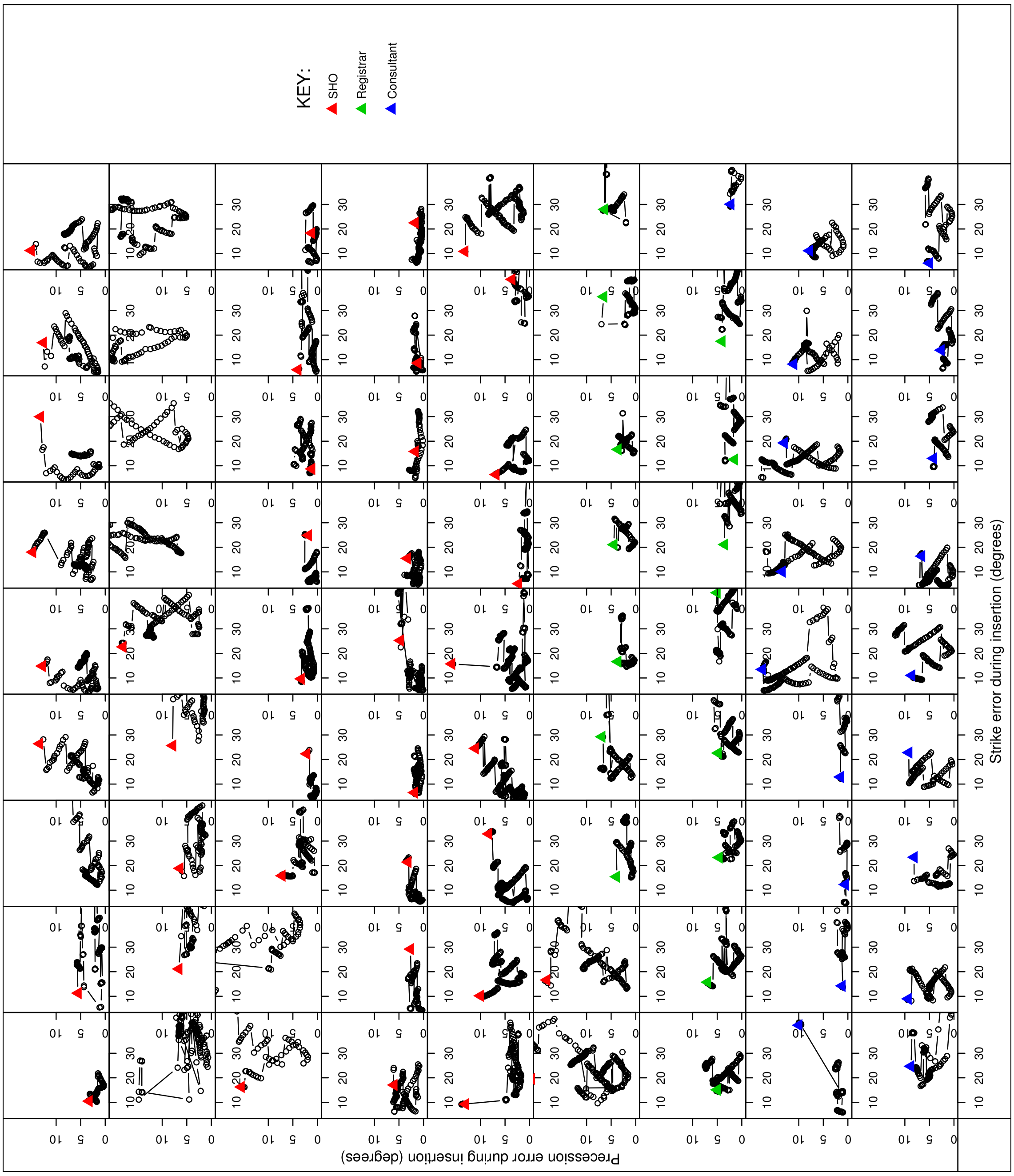


Figure E.2: Correlation between errors using Test C results at fixed scales

(Note: alternate trials are indicated by circle and square symbols in the plots; coloured triangles indicate the start point of each sequence.)

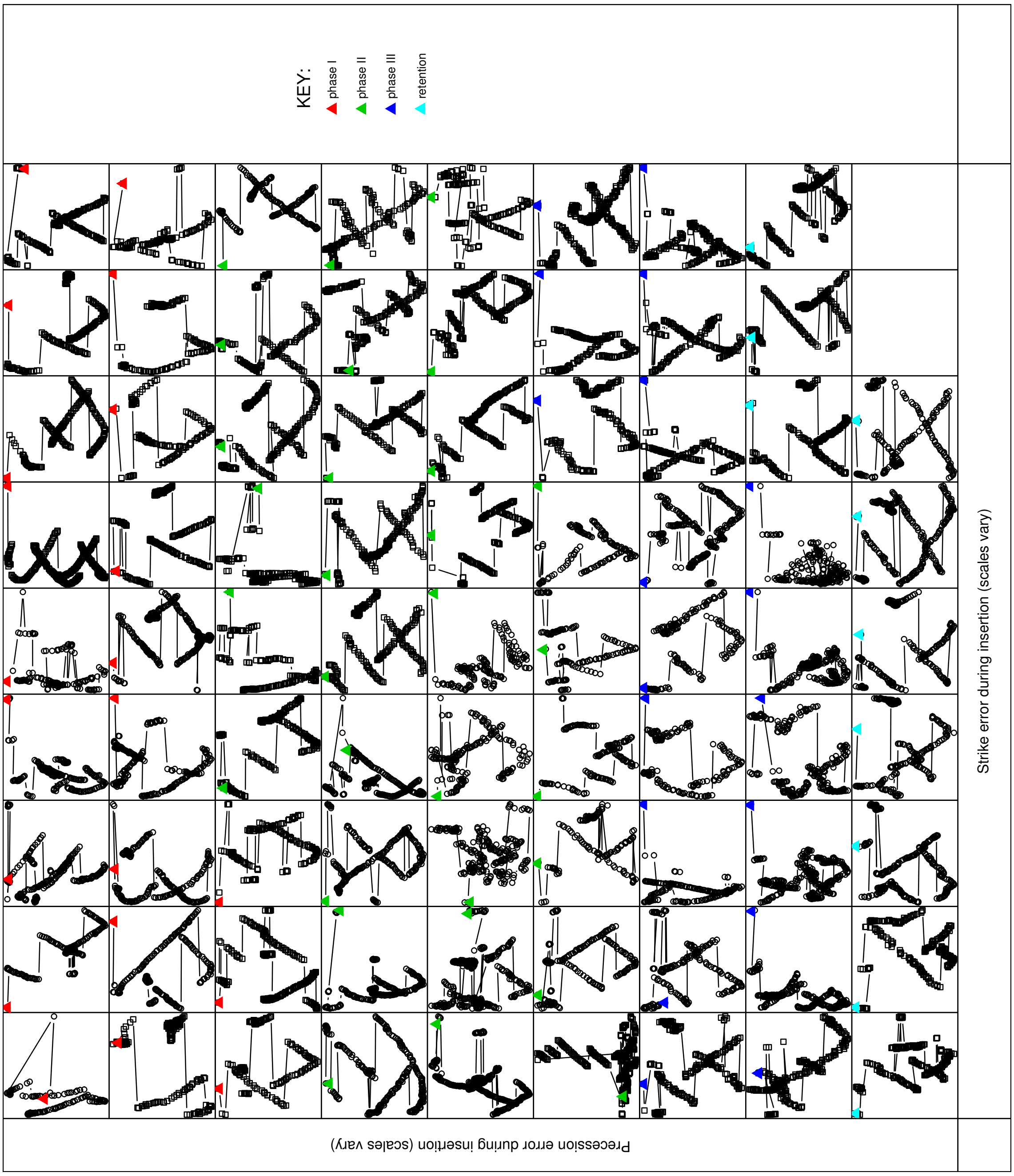


Figure E.3: Correlation between errors using Test A results at varied scales

(Note: alternate trials are indicated by circle and square symbols in the plots; coloured triangles indicate the start point of each sequence.)

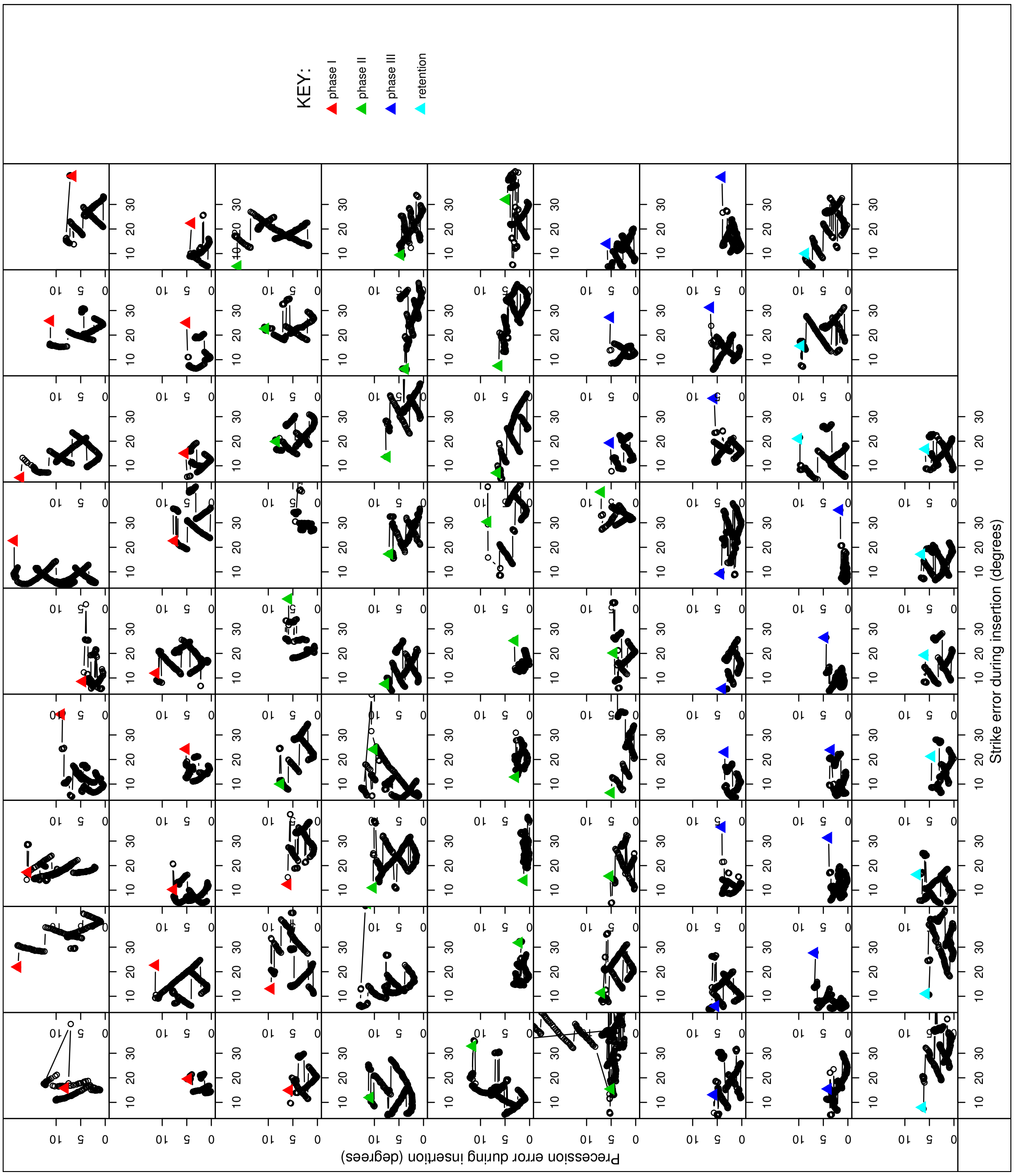


Figure E.4: Correlation between errors using Test A results at fixed scales

(Note: alternate trials are indicated by circle and square symbols in the plots; coloured triangles indicate the start point of each sequence.)

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