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GLOSSARY

Construct validity is the extent to which a test measures the trait that it purports to measure. One inference of construct validity is the extent to which a test discriminates between various levels of expertise.

Content validity is the extent to which the domain that is being measured is measured by the assessment tool—for example, while trying to assess technical skills we may actually be testing knowledge

Concurrent validity is the extent to which the results of the assessment tool correlate with the gold standard for that domain

Face validity is the extent to which the examination resembles real life situations.

Femoral Neck Fracture is more commonly called a hip fracture, and involves a break in the top of the thigh bone.

Haptics refers to the science of supplying touch (tactile) sensation to the user, such that the user can feel a virtual object. This utilises devices such as joysticks or datagloves.

Laparoscopic is commonly called keyhole surgery. This involves a fibre-optic scope and camera to allow surgery through small incisions.

Render is the term used to describe how a computer draws an object on the monitor.

Predictive validity is the ability of the test to predict future performance.

Inter-Rater or Inter-Observer Reliability. Used to assess the degree to which different raters/observers give consistent estimates of the same phenomenon.

Test-Retest Reliability. Used to assess the consistency of a measure from one time to another.

Internal Consistency Reliability. Used to assess the consistency of results across items within a test.

VRML stands for Virtual Reality Mark-up Language, similar to HTML but describes objects in 3 dimensions

From Plato's Phaedrus comes the story of Thamus. Thamus was a king in a great city in Upper Egypt. He was critiquing the inventions of a god called Theuth. These inventions included number, calculation, geometry and writing. Introducing his invention writing, Theuth announces, "Here is an accomplishment, my lord the King which will improve both the wisdom and memory of Egyptians. I have discovered a sure receipt for memory and wisdom"

Thamus replies, "Theuth, my paragon of inventors, the discoverer of an art is not the best judge of good or harm which will accrue to those practice it. SO it is in this; you, who are the father of writing, have out of fondness for your off-spring attributed to it quite the opposite of its real function. Those that acquire it will cease to exercise their memory and become forgetful; they will rely on writing to bring things to their remembrance by external signs instead of by their own internal resources. What you have discovered is a receipt for recollection, not for memory. And as for wisdom, your pupils will have the reputation for it without the reality: they will receive a quantity of information without proper instruction, and in consequence be thought very knowledgeable when they are for the most part quite ignorant. And because they are filled with the conceit of wisdom instead of real wisdom they will be a burden to society"

Phaedrus p96, by Plato

Chapter 1

1 INTRODUCTION

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

Surgical training is showing signs of changing from an apprentice-style approach to a curriculum based method. Co-existent with a curriculum based method is the desire to provide a consistent experience for all trainees. Simulation is one method of providing this consistency. Virtual reality simulators have been a fascinating idea for some time, though simulators have only recently been available in surgery, and most commonly in general surgery.

This thesis describes the development of a virtual reality surgical simulator for orthopaedic surgery. Modules were developed for two types of hip operations. The aims of this research were as follows:

- To investigate the attitudes towards simulation within the orthopaedic surgical community.
- To design and develop a virtual reality simulator for some examples of hip surgery.
- To validate the simulator in a number of ways.
- To test the ability of the simulator to be used for assessment within orthopaedic training.

The attitudes of the orthopaedic surgical community were sought for a number of reasons. Firstly to identify whether the community felt there was a need for simulation, as this impacts on how much support there would be for incorporating simulators into training and continuing education. Secondly to identify the level of computer literacy within the community, this partially dictates the level of sophistication of the simulator interface. Finally questions identifying specific tasks or procedures were asked. This was in order to see how closely aligned the simulator which was concurrently being developed matched the perceived need.

As there was no virtual reality simulator for image guided orthopaedic operative procedures, part of the work towards this thesis involved designing and then programming a virtual reality simulator for hip surgery. The design constraints consisted of such things as making the simulator work using the computers found within the hospital system, thus enabling trainees to access the simulator at work, rather than travelling to a simulation centre. Other issues were incorporating the necessary decision-making steps within the operation, balancing the level of detail with the performance capabilities of the hardware and software systems and making allowances for trainees with different levels of computing experience.

Having designed and programmed the simulator, the next crucial factor involved validating the simulator. This validation should be done prior to using a simulator within training and/or selection of trainees. There are a number of different ways simulators can be validated. Face validation involves identifying how closely the simulation resembles the real procedure. A measure of construct validity is the ability of a simulator to discriminate between users with different levels of surgical experience. Transfer validity aims to determine how skills honed in a simulation environment improve performance in the clinical setting. This type of experiment is significantly more difficult to perform as there are a number of confounding factors such as obtaining an objective score for real world operative performance.

Major factors influencing the uptake of simulation technology include the ease with which the simulator can be incorporated into the training curriculum, and whether the simulator presents a challenge for the trainees. To this end the procedure of screw fixation of a slipped capital femoral epiphysis was simulated, and the simulator tested within one of the biannual training weekends, which are organised for all New Zealand orthopaedic trainees.

The originality of this work lies in its novel method of creating a surgical simulator for orthopaedic surgery, suitable for use on computers found in the current public health system. Rather than relying on high-tech hardware, such as haptic (force feedback) devices, the simulator uses a software based approach, which is both cross-platform as well as backwards compatible to early versions of computer operating systems. The focus of the simulator is on enabling trainees to practice angulations and the x-ray appearance of their guide-wires, without exposing patients to risks or the trainees to ionising radiation.

The work presented here represents the beginnings of how this simulator can be used for selection of trainees, training for new procedures, and assessment of how well trainees are progressing. The process of selecting trainees is becoming more topical as selection committees explore new methods to increase the objectivity with which trainees are chosen. Further improvement of patient care and legal defence of the selection criteria, are the main drivers for improving this objectivity. Training methods are becoming more topical as the public take a greater interest in the medical profession. Some no longer wish to be 'practiced upon' and others are challenging the concept of apprentice-style training. Assessment of performance may in time be more topical if colleges are challenged legally for failing to produce surgeons qualified to perform safely. These challenges may arise as limits on work-hours force a reduction in exposure of trainees to operative cases.

1.1 Publications Arising

The research presented in this thesis has resulted in five papers to date. These papers have either been published or submitted for publication to peer reviewed journals:

1. Blyth P, Anderson IA, Stott NS. Virtual reality simulators in orthopedic surgery: what do the surgeons think? J Surg Res 2006;131(1):133-9.

2. Blyth P, Stott NS, Anderson IA. A simulation-based training system for hip fracture fixation for use within the hospital environment. Injury 2007;38(10):1197-1203.

3. Blyth P, Stott NS, Anderson IA. Virtual Reality Assessment of Technical Skill using the Bon*e*doc DHS Simulator. Submitted to Injury.

4. Blyth P, Stott NS, Anderson IA. Virtual Cannulated Screw Fixation of Slipped Capital Femoral Epiphysis by Orthopaedic Surgery Trainees. Submitted to Journal of Bone and Joint Surgery.

5. Insull P, Kejriwal R, Segar A, Blyth P. Surgical inclination in senior medical students from the University of Auckland: results of the 2005 Senior Students Survey. N Z Med J 2006;119(1234):U1983.

1.2 Conference Presentations

Aspects of this work have been presented at a number of international conferences. These include:

1. Blyth P, Fernandez JW, Thrupp S, Anderson IA, Hunter PJ. Utilisation of VRML to Access a Cubic Finite Element Model of the Lower Limb to Teach Anatomy and Simulate Dynamic Hip Screw Placement. In: 4th Visible Human Conference; 2002 17-19 October 2002; Keystone, CO, USA; 2002. www.uchsc.edu/sm/chs/events/vh_conf/pdfs/039.pdf

2. Blyth P, Fernandez JW, Thrupp S, Anderson IA. A Method for Rapid Production of Patient Specific Femur Models. In: 51st Annual Scientific Meeting of New Zealand Orthopaedic Association; 2002 20-23 October 2002; Palmerston North, New Zealand; 2002. In: J Bone Joint Surg Br 2003;85-B(SUPP_III):p204.

3. Blyth P, Anderson IA, Stott S, Hunter PJ. Operating in a Virtual Theatre. At: 4th APEC Science Ministers Meeting (Innovation Showcase); 2004 9-11 March 2004; Christchurch, New Zealand; 2004.

4. Blyth P, Fernandez JW, Thrupp S, Anderson IA. A Method for Rapid Production of Patient Specific Femur Models for use in Virtual Surgery. In: 16th International Congress of the IFAA (International Federation of Anatomical Associations); 2004 22-27 August 2004; Kyoto, Japan: Blackwell Publishing; 2004. p. 342.

5. Blyth P. Use Of Virtual Reality For Teaching Difficult Anatomical Concepts. In: 2nd Annual Conference of the Australian and New Zealand Association of Clinical Anatomy; 2005 2-3 September 2005; Dunedin, New Zealand: In: Clinical Anatomy; 2005. p. 172.

6. Blyth P, Stott NS, Anderson I. Virtual Reality Simulators in Orthopaedic Surgery, What do the surgeons think? New Zealand Orthopaedic Association, Annual Scientific Meeting; 2005 2-5 October 2005; Christchurch, New Zealand; 2005. In: J Bone Joint Surg Br; 2006 May 1, 2006; 2006. p. 320.

7. Blyth P. Virtual Trauma. Injury 2005; 2005 4-5 August 2005; Auckland, New Zealand; 2005.

8. Blyth P, Stott NS, Anderson IA. Development and Face Validity of a VRML simulator for Hip Fracture Fixation. In: Medicine Meets Virtual Reality 15; 2007 6-9 February 2007; Long Beach, California; 2007.

1.3 Descriptions in the Media

The work has been reported in a number of different media, these include:

1. TV1 Network News. APEC meeting reports. TVNZ 10 March 2004.

2. Devereux M. Surgery simulator a risk-free trainer. The New Zealand Herald 2004 23 March 2004.

3. Dunning J. Simulator. Radio Rhema; April 2004.

4. Griggs K. Doctor Doctor A simple programme is reducing surgical training costs and risks. Unlimited 2004:17.

5. Meduna V. Virtual simulator for broken hips. In: Eureka. Auckland: Radio New Zealand; 2004.

6. Cyberworld. Taputapu Hou. Maori Television. June 2005.

C h a p t e r   2

2 BACKGROUND

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

2.1 Introduction

This chapter describes the history of simulation, different types and examples of simulators, validation of simulators, the real world issues and virtual reality options. Knowledge of the history of simulation from aviation and other surgical specialities provides a means to learn from their examples and helps to provide support with challenges common to different simulators. An understanding of the various types of simulators facilitates the identification of the best method for training in a specific task. With this understanding a simulator can then be validated to assess how well it allows trainees to up-skill in these tasks. The chapter finishes with discussion about the real world issues within training, the patients and trainees, as well as the complexities of using a virtual reality solution for these problems.

2.2 Simulators

Acquisition of technical expertise is a vital yet complex goal of surgical training. There are a myriad of options to achieve this goal. However it is well understood that this acquisition is dependant on practice. Immediate feedback and graduated increasing complexity of task/s are two factors known to improve quality of practice and reduce the quantity of practice required to obtain expertise in a specific area (Ericsson, Krampe, & Tesch-Romer, 1993; Guest, Regehr, & Tiberius, 2001). It is often difficult in surgical training to provide trainees with immediate feedback and graduated complexity of operative cases. Simulation of surgical procedures thus is a potentially attractive option to provide these elements, within a risk-free environment.

2.2.1 History of Simulators

Flight simulators have been around since before First World War, inspired by the need to practice a task without placing expensive equipment or personnel at risk.

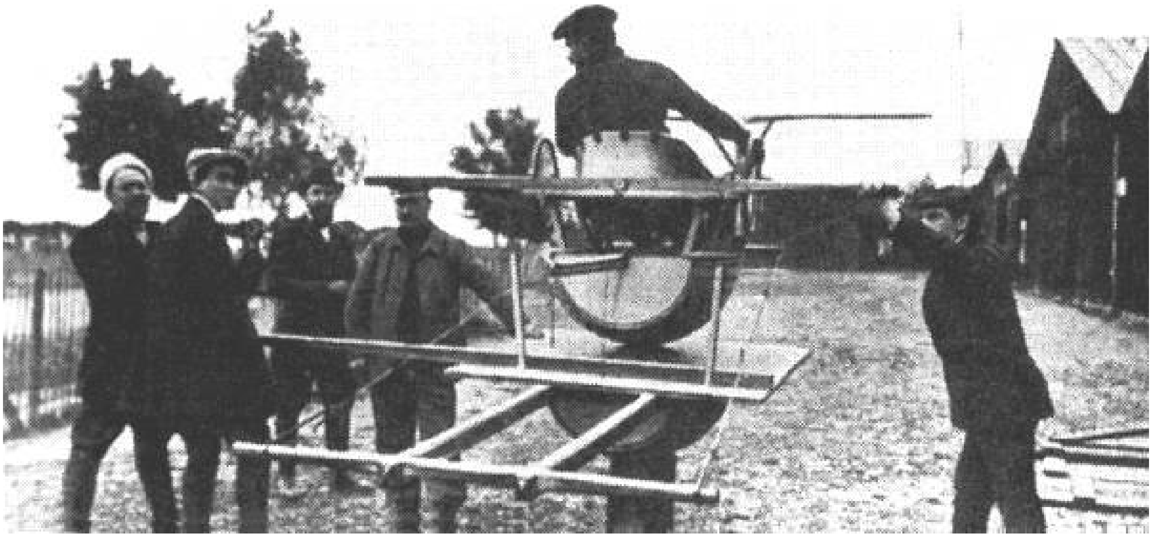

FIGURE 2.1: An early flight simulator, the supervisor moves the aircraft in pitch and roll in response to the pilot's action on the joystick. Published in the Antoinette catalogue 1910. Accessed at http://homepage.nthworld.com/bleep/SimHist1.html

Figure 2.1 shows simulation in use only 7 years after Orville Wright's controlled powered flight on 17th December 1903.

During the 1960's flight simulators became an integral part of commercial airline operations as the focus on safety and training effectiveness, made it no longer feasible to practice in real aircraft. In 1967 virtual reality was incorporated into flight simulators. These first simulators were used in the training of military and air-force personnel.

In 2008 all Air New Zealand pilots spent 2 days per 6 months in simulation training. The first time a pilot flies in a new class of plane, the plane will be fully loaded with passengers and cargo. However by this stage he/she will know how the plane responds if an engine fails, and will have successfully landed that plane on the 'virtual runway'. Interestingly as in medicine, the passengers will most likely not know that this is the first time the pilot has flown that aircraft type.

Simulation within medicine is some decades behind the aviation industry. Since 2000 there have been increasing efforts and focus on simulation, though crude simulators have been used since the 16^{th} century to teach obstetrics(Buck, 1991). Simulators were first introduced in anaesthetics and cardiopulmonary resuscitation training with "Resusci Annie" which was created by Asmund S Laerdal in 1960. An obvious requirement for the manikin is a realistic face, and this was based on a death mask from the "Girl from the river Seine" who drowned at the turn of the 19th century.

Within the surgical arena, virtual reality (VR) surgical simulation for minimally invasive vascular procedures is probably the most advanced. Currently the US Food and Drug Administration (FDA) requires VR simulation as part of the training for endovascular carotid stent placement (Gallagher & Cates, 2004). This move represents a significant milestone towards the use of virtual reality in surgical training.

Within orthopaedics, non-computerised simulation has been used extensively in training, Sawbones® workshops have been used for the past 25-30 years (www.sawbones.com). Computers have been used in orthopaedic surgery since the introduction of ROBODOC® (www.robodoc.com) in 1992. The ROBODOC® system uses CT scans to preoperatively plan surgery for hip arthroplasty. The computer is coupled to a robotic arm, which precisely mills the femoral canal to the shape of the femoral prosthesis(Schulz et al., 2007). Thus training has largely been performed in the real world, while pre-operatively planning has occurred in a virtual environment. Virtual Reality orthopaedic surgical simulation started with Knee arthroscopy simulators such as the Boston Dynamics Arthroscopy Knee Simulator(Poss et al., 2000). Simulators such as this have attempted high-fidelity simulation, using haptics (force feedback).

FIGURE 2.2: A Sawbones® model with a mid-shaft femoral fracture.

2.2.2 Turing Test

A landmark paper published in 1950 entitled "computing machinery and intelligence" by AM Turing on artificial intelligence describes The Imitation Game(Turing, 1950). This is played by three people, a man, a woman and an interrogator. The object of the game is for the interrogator to determine which of the other two is the man and which the woman. Communication is via typewritten questions and answers. In due course the man is replaced by a machine, and if the interrogator decides wrongly about the identification as to who is the woman, equally as often as when the choice was between man and woman then the machine has passed the test.

Modern variations of the test describe a single room with either a human or machine, and the interrogator deciding on whether the subject is human or not. This has advantages in that no longer are you including the fact that both man and machine are 'playing out of character'. This modern variation makes it harder for the machine.

A similar test could be performed with simulation. If a subject performs surgery in both the real and virtual world and is unable to tell which world they are in then this would satisfy the "Turing Test". This amount of realism could challenge our definition of reality, and extreme caution would be needed to ensure that all consequences were simulated, otherwise trainees could be attempting risky manoeuvres in real life, having performed them in the simulated world.

An important part of Turing's Imitation Game is that the communication was typewritten to remove the clues given by vocal intonation and appearance. This is important because the question the imitation game is trying to answer is about logic rather than merely appearance.

Another means of aligning a simulator test with the Turing Test is to judge the candidates performance in the same manner as they are judged in the real world. Thus an external interrogator must look at the results of the simulation and the real procedure and not be able to tell which was performed on the simulator. This requires that similar performance parameters be provided such as x-ray views at the conclusion of the procedure, examples of how trainees misplace screws, time to perform the operation, x-ray exposure and length of skin incision.

2.2.3 Cost

The financial drive of present day economies and the strength of technology and communications make it difficult to attract people's attention and unless a technology is perceived to be cutting edge, it is often seen as worthless. There is no comparison between the crude surgical simulators currently available with the sophisticated simulators of the airline industry. However allowances must be made in order to allow refinement of simulators, with attention paid to the drivers for this ongoing development.

When flight simulators were initially developed, the aircraft they were mimicking were relatively crude, thus facsimiles of instruments were reasonably easy to create. If airline simulators were in their infancy now, it is easy to imagine them taking some time to mature. Initial drivers for development of simulators within the air industry were a lack of planes within the Second World War, as well as the fact that if you crashed there was a fair chance of killing yourself. Pilots were forced to train on the simulators as there was neither the time nor hardware to practice any other way. Currently there is no requirement for holders of private pilot's licenses to spend time in a simulator. This may be in part due to the fact that small planes are plentiful and relatively cheap, but also the availability of instructors means that it is much more expedient to spend time in the plane with the instructor than on the ground in a machine. However the economics of commercial planes dictates that the cost of using an aircraft for training would cripple any airline. Training on a flight simulator encourages pilots to use less fuel, and to avoid manoeuvres which place undue stress on the aircraft, consequently reducing down-time for maintenance of the aircraft. The airlines use the simulator to save money.

By comparison, the public surgical world has an abundance of patients. The health model is basically a cost model whereby the less surgery performed the more money saved by the health system. The extent to which public health systems are overburdened is reflected by the development of scoring tools to prioritise access to elective services by patients(MacCormick, Collecutt, & Parry, 2003). The complex logistics of getting patients to theatre and predicting the length of time the operation will take, mean that any gain by a surgeon resulting in an operation finishing slightly faster, may just result in the theatre staff finishing slightly early, without the possibility of doing another case. In this manner a simulator might improve surgical time, though still not result in any more profit to the organisation. Less complications would have benefits to the organisation, however as described later, it is difficult to prove this effect.

Commercial simulators can enable pilots to fly more safely, and also more economically. The Federal Aviation Authority (FAA) has a responsibility to ensure safety, and endorse simulation as a means of training and assessing pilots. This governing oversight means that simulation will continue to flourish within the airline industry. The economic cost of a pilot crashing a plane means that airlines are committed to spending large amounts of money on simulation to ensure this does not happen. In contrast the economic costs of surgeon error are borne either by the government in NZ, or by medical indemnity programmes (which in turn are funded by surgeon subscription).

2.2.3.1 Cost of attending workshop.

The small workforce means that it is often difficult for trainees to get time off clinical work to attend surgical workshops, and the large amount of after-hours work, make weekends precious. In addition there is the cost of accommodation if the course is in a different city and the logistics of finding cover if a number of trainees from one hospital attend a workshop. However although these are significant barriers to attending workshops, the courses are highly valued by the trainees due to their relevance to the work. There are a number of workshops which basic trainees in NZ currently attend, these include EMST (Emergency Management of Surgical Trauma) and CCrISP (Care of the Critically Ill surgical Patient). Health boards will often pay for these workshops as part of their investment in training because the courses are prerequisites for entrance to advanced training. Thus there are opportunity costs for the trainees, and some competition between courses for a slice of the education budget of the health boards.

2.2.3.2 Cost of hiring ancillary personnel to run simulation.

Most courses rely on surgeons to instruct on the courses. This is a very worthwhile aspect of the courses, as it fosters the role of surgeons as mentors for the trainees, as well as ensuring that material taught on the courses is both relevant and up-to-date. However the logistical aspects of getting surgeons to attend courses outside of working hours, and often as volunteers, means that any course which runs several times a year has to have a pool of surgeons to select from in order to avoid burn-out of these committed teachers.

2.2.3.3 Cost of ongoing materials.

The price of disposable materials can be a significant part of the budget of many courses. Currently most materials within surgery are designed as single-use items. Although this provides ease of use within surgery, it means that items often cannot be used within workshops more than once, adding significantly to the cost.

2.2.3.4 Groups capable of paying for a simulator.

Within New Zealand there are six main groups which could be responsible for supporting simulators, these are the Government, Medical Councils, Surgical Colleges, hospitals, implant manufacturers and individuals.

At present there are very few simulators which are validated enough to sway groups such as government, medical councils, or surgical colleges to support or mandate a simulation requirement in training. Currently it is senior medical staff within hospitals that are moving towards simulation as a means of up-skilling their doctors. However the core business of hospitals is not education of its staff, and consequently the budgets of surgical skill centres reflects this. A majority of surgical skill centres are set up with grants which provide relatively large start-up funding but little ongoing funding. This style of funding makes virtual reality simulation more attractive than manikin style simulation, as there are less ongoing costs for disposables. However the price of any simulator must be weighed up against its usability, thus if a simulator can be used for numerous scenarios then it is much more effective than a simulator which can only replicate a single scenario.

As surgical implants become more sophisticated implant manufacturers are becoming more aware of the need for education. Trainees who learn with a set of instruments from a particular manufacturer are more likely to request those instruments in their practice, due to their familiarity.

This finally leaves the individual, who has the most to gain from the simulator, but has the least means of paying for the simulator. Added to this the individual has the least time, and the opportunity cost of spending time on a simulator means if there is more to be gained by reading journal articles or texts they are more likely to pursue this form of education.

2.2.4 Types of simulators

Simulators can be divided into those which simulate the entire task or those described as part task trainers.

2.2.4.1 Entire task trainers

Entire task trainers teach all aspects of a procedure. This may involve the communication between members of the surgical team, selection of appropriate instruments and performing the surgical task.

Entire task trainers can be further divided into those involving the complete team, and those where only a small part of the team is included. Obviously simulators which utilise the full team are more likely to approximate the real procedure but there is a significant opportunity cost of having the full team represented. It is for this reason that most Advanced Trauma Life Support/Emergency Management of Surgical Trauma courses utilise faculty to 'stand in' and undertake role-play. Simulators which do not use the full team, or in fact are run by only one member of the team can still improve the real world performance by using other members of the team to act in the role of another member. This use of role play also helps communication between team members(Carley & Driscoll, 2001).

Most simulators are support intensive, whereby a large number of people, and surrounding ancillary equipment are required to run the simulation. For this reason virtual reality options are being explored in a number of institutions. These simulators have the advantage of relatively low ongoing costs.

2.2.4.2 Part task trainers

The limits of working memory are classically described in George Miller's paper "The Magical Number Seven, Plus or Minus Two"(Miller, 1956). Chunking theory was first described by Herbert A. Simon to explain how by packaging hierarchies of information into chunks, people are enabled to overcome the limits of working memory (Gobet & Simon, 1998). In a similar manner, part task trainers divide the procedure into defined key components, such as how to make an incision, how to place a lag screw, and how to suture. This allows trainees to become proficient in one area, before attempting the entire procedure. This method is commonly used within VR simulators such as the LapSim system(Woodrum et al., 2006) whereby trainees need to achieve a set standard at one task before they are allowed to progress to the next. Trainees may become disillusioned with the task trainer if they see no inherent value in perfecting that step or the means of scoring is not seen as approximating real world values. Thus by using a quasi-result to prevent trainees from progressing to the next level, the trainee who feels they have passed the procedure as a whole is less likely to keep training on the simulator. Often these part-task trainers are somewhat removed from the real surgical procedure, with the result that trainees lose sight of the potential benefits from the simulator.

Assessment of overall real world surgical performance is very complex, due to the variability in patients, diseases, surgeons, and hospital systems. The effect of the surgical environment on outcome is well described in the literature. Increased hospital procedure volumes is associated with fewer complications(Shervin, Rubash, & Katz, 2007), although generally surgeon volume has a greater positive effect than hospital volume. Thus, overall surgical performance assessment remains reliant on many variables, as well as being somewhat subjective. Hence quantification of overall performance assessment remains elusive, and any system of using simulators for accreditation must make allowances for variations to individual subjects performance.

There are a number of different methods available for either teaching the entire task or simply a small part thereof. These will be described in this next section.

2.2.5 Alternatives to Virtual Reality

2.2.5.1 Cadaveric workshops

Cadaveric human tissue is available from anatomical schools, though availability will be governed by the local Human Tissue Act. Within the simulation literature cadaveric models are usually described as either expensive, or have significant barriers to access. However these may be perceived rather than real problems. If the overall cost of running surgical courses is examined, there are often significant costs in shipping sets of instruments to the site, or faculty members to run the course, thus the cost of the cadavers may not actually be that high.

An issue in cadaveric workshops is that of consistency or availability of human tissue at the different course sites. In addition, increasingly there are requirements to keep course instrument sets separate from those used within the hospital environment, although the same can be said for instruments used in animal workshops.

Perhaps the greatest barrier is access to human tissue suitable for skills workshops. This is dependant both on the local anatomy department and the availability of suitable embalming techniques. Usually departments of anatomy are keen to foster relationships with surgeons and surgical courses, but do not necessarily have the contacts. The methods of preservation of tissue ranges from fresh frozen tissue, through to tissue embalmed using a number of different methods.

Fresh frozen tissue is currently the gold standard for cadaveric human tissue for surgical skills workshops. The downsides to fresh frozen tissue from a surgical point of view include the increased exposure to infectious agents, though most laboratories will perform serological testing prior to use. From a laboratory point of view, freezer space can be an issue. The opportunity cost of using a cadaver for a specific workshop may mean that it is not available for other applications, due to the limited number of times the tissue can be thawed and refrozen. In addition there is the requirement to have available enough limbs for a given workshop, and then having the facilities and personnel to thaw the tissue adequately prior to the workshop.

The Graz embalming technique was developed by Walter Thiel in Graz, Austria(Thiel, 1992). This technique relies on a combination of 4-chloro-3-methylenphenol, various salts, boric acid and ethylene glycol. The cadavers are stored at chilled temperatures. The tissue is incredibly flexible, such that for a lumbar puncture workshop the cadaver's forehead will usually touch the knees. The tissue planes are easily identifiable. Tissue colour is remarkably close to living. The negative aspects of this embalming technique are the requirements for mixing of the chemicals during embalming, and keeping the supersaturated mixture from depositing in the embalming pump. In addition the keratinized layer of skin and hair sloughs during the process, with the result that this layer needs to be removed prior to use. When the tissue is exposed to air for longer than ~2 hours the tissues darken remarkably. This can be prevented by keeping the tissue moist.

The Dodge method uses a proprietary solution from The Dodge Company (Massachusetts, USA), this solution comes ready mixed and relies on a low concentration of formaldehyde. The cadavers embalmed with this method are stored at chilled temperatures. The tissue is relatively flexible, and tissue planes are somewhat identifiable. The tissue colours are relatively vivid. There are minor problems with mould.

The Genelyn method is based on proprietary ready mixed solutions developed and manufactured in Australia (www.genelyn.co.au). This solution relies on a low concentration of formaldehyde. The cadaveric tissue can be stored at chilled temperatures. The tissue is similarly or perhaps slightly more flexible than the Dodge. The tissue planes are similar to that of Dodge anatomical mix. The colour of the tissue is not as remarkable, though there are fewer problems with mould.

Many medical schools use traditional embalming methods developed in-house. These methods use either formaldehyde or phenol and are mixed within anatomical departments according to their specific protocols. The negative aspects of these methods include relative tissue inflexibility, and lack of colour, the carcinogenic nature of these compounds and the particular odour. However there are seldom problems with mould. These negative aspects often make this tissue relatively unusable for workshops and can permanently deter surgeons from using cadaveric specimens in future workshops.

2.2.5.2 Animal Workshops

Animal workshops are used mainly for soft tissue workshops. For this purpose they are ideal in providing realistic texture and flexibility of the soft tissues and are ideal for learning placement of sutures. In addition they provide the opportunity to assess such skills as anastomotic (joining of two hollow organs or vessels) technique which rely on ensuring there are no leaks. However differences in bony anatomy means animal models are not really suitable for learning techniques such as intramedullary rod fixation, or plate placement. In addition animal rights movements are placing increasing pressure on course convenors not to use animals for such purposes.

2.2.5.3 Synthetic materials simulators

Development in Synthetic materials simulators is gaining momentum. Advances in material sciences mean that synthetic materials are becoming increasingly similar to the tissues they are replicating. An example is the Zurich heart-trainer (Reuthebuch et al., 2002). This is manufactured from differentially hardened polyurethane. It may be connected to pumps, such that it beats in a realistic manner, the coronary arteries can be filled, enabling anastomotic technique preparation, and there is no problem with storage or exposure to infectious material. However the cost of synthetic material simulators must be taken into account as many articles are single use. As discussed many surgical simulation centres suffer from the problem of receiving initial large capital investments, but little ongoing support, leaving these centres unable to use these simulators. Often the best solution is somewhat simple, an example of this is a simulator utilising a normal webcam and computer(Chung, Landsittel, Chon, Ng, & Fuchs, 2005; Pokorny & McLaren, 2004). This system is easily able to teach the fulcrum effect of laparoscopic surgery, at a fraction of the cost of a virtual reality or even a laparoscopic setup, with the advantage that the instruments are identical to those used in surgery, even if the camera and tissues are not.

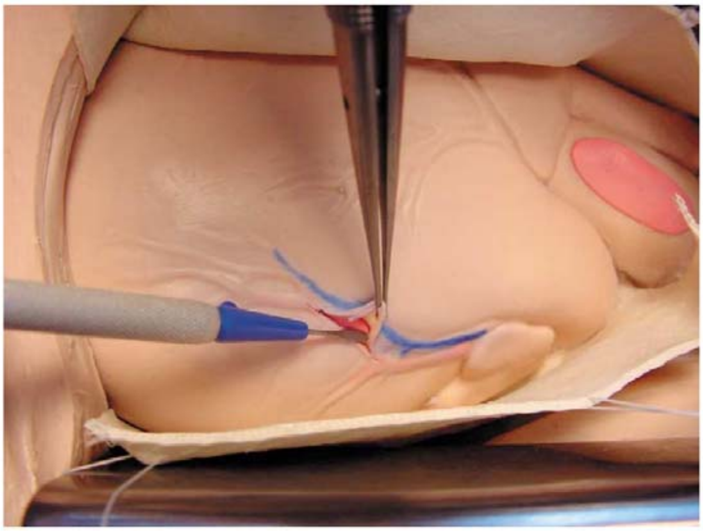

FIGURE 2.3: A Heart made of synthetic materials. Image from Reuthebuch et al (2002).

2.2.6 Virtual reality simulators

Against this backdrop of inaccessible human or animal tissue, risks of infection, and ongoing costs of consumables, virtual reality appears to offer a number of benefits over other alternatives for simulation. This section will describe a number of different aspects of virtual reality simulators, including the common perceptions of what virtual reality means, such as haptics and stereoscopic vision.

2.2.6.1 Haptics

Haptic comes from the Greek word "haptein" meaning touch. Within the VR simulation world this has come to mean force feedback, such that through a user interface the user is able to feel the shape or texture of a virtual object. Enabling a hardware interface to mimic the real world is a non-trivial problem. This problem can be broken up into various components. These components include the physical characteristics of the user interface, the fidelity of the underlying model, the ability to match the location of the device/users hands with the visual location of the same, the ability of the simulator to take sense input from the haptic device and adjust the scene and ease of setup and cost.

An example of a haptic device is the Phantom Omni (Sensable technologies®, Woburn, MA, USA), costing around NZ$4000. This device has a pen-like stylus which the user holds. It senses the position of the tip of the stylus with 6 degrees of freedom, and can produce force feedback in 3 dimensions, which is akin to the feedback you would feel with the tip of a pencil.

FIGURE 2.4: The Phantom® Omni™ haptic device senses 6 degrees of freedom, and can produce a force with 3 degrees of freedom.

The physical characteristics which apply to all haptic devices include the refresh rate at which the device can provide the feedback force, the working area of the device, the amount of force the device can produce, the background inertia of the device, the resolution of the device, the number of degrees of freedom the device can sense and provide force feedback, and finally the ease of use.

The refresh rate of the device needs to be at least 1-2 KHz, as below this there is a feeling of vibration or buzzing. Implicit within this is the requirement for the virtual model to be updated as a result of the user interaction. The display only needs to update at 30Hz for motion to be perceived as fluid, thus there has to be some method of integrating these two threads.

The amount of force the device is able to deliver can be important in some instances. An example of this is the use of hammers in orthopaedics. One would not want a haptic device malfunctioning and driving the device in the wrong direction, causing a shoulder dislocation or otherwise injuring the trainee. The simulator does however need to be able to provide a realistic amount of force.

Thus if the surgeon is holding a drill and can overcome the force provided by the haptic device, then a break with "virtual reality" occurs and the surgeon no longer feels "immersed" in the simulation. Another virtual problem occurs if inadvertently the simulator allows the drill tip to end up on the intramedullary side of the bone without having drilled. Such an occurrence could be due to a "gap in the mesh". There has to be a means of returning the drill to the side on which normal physical properties apply. Any forces which are felt during this phase substantially contribute to confusion on the trainee's part, and can prevent them from perceiving the simulation as real.

Another aspect of orthopaedic surgery is the diversity of instruments used, as can be seen in TABLE 2.1, ranging from scalpels, through to forceps, drills and hammers. Thus there are instruments with widely differing requirements for force generation and the number of degrees of freedom required. Usually the greater the feedback force the haptic device can deliver the greater the inertia of the device, making a device capable of delivering large forces unworkable for fine movements. For a surgical procedure the options involve either using five different haptic devices or a single device with an interchangeable head. If a single device with multiple heads is used, there is the problem of calibrating the device, in addition instruments such as forceps or drills need additional degrees of freedom or switches.

During orthopaedic surgery to fix a fractured neck of femur, the surgeon will employ a number of different modalities, which have specific requirements from a force feedback viewpoint. Assuming the patient is already placed on the traction table, the surgeon will first reduce the fracture. This reduction is achieved by altering the traction table. To enable simulation of this process of reduction you would need to provide the surgeon with a number of levers, as well as knobs and screws, each of these will have specific torques dependant on the amount of distraction or angulation.

FIGURE 2.5: The traction table, showing the various levers and knobs used to adjust the position and angulation of the limb.

Following reduction of the fracture the surgeon will palpate the bony prominences under the skin. This is done with either an ungloved hand on skin at the start of the procedure, or a double gloved hand on a plastic adhesive drape during the procedure. Following palpation, the surgeon may mark with an indelible pen the angle which they will subsequently place the guide-wire in. The next step is prepping skin with a gauze "swab on a stick". Following draping, an incision is made with the non-dominant hand gently spreading the cut skin edges. A self-retaining retractor is used to retract the skin edges. Scissors are used for first blunt then sharp dissection through the fascia lata. Following this the vastus lateralis muscle is split and using the periosteal elevator the muscle is cleared off the lateral surface of the femur.

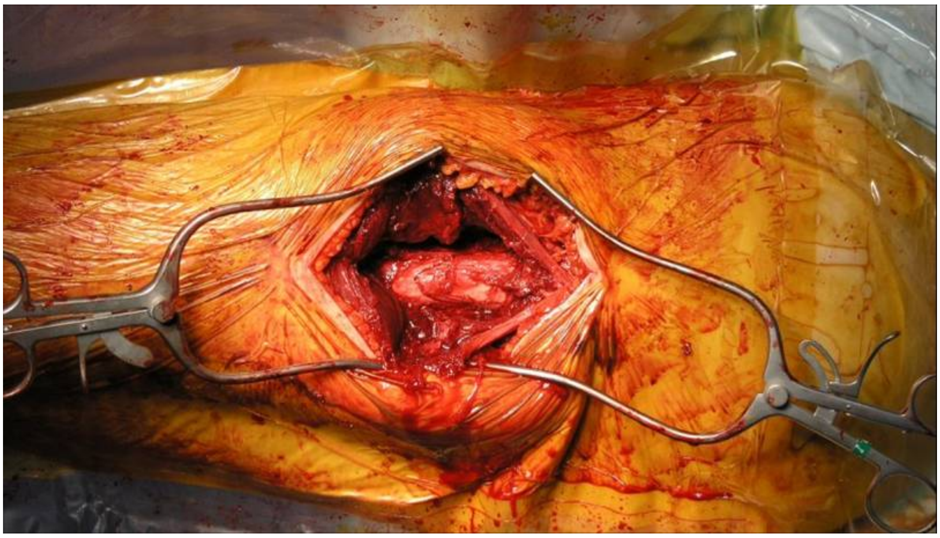

FIGURE 2.6: The surgical view having incised the vastus lateralis muscle.

The femur is exposed, and a cordless drill is used to drill the guide-wire into the femoral neck and head. An image-intensifier (type of x-ray machine) is used to guide the correct placement of this guide-wire. This is a key element of the procedure and will be discussed in depth in later sections.

FIGURE 2.7: The image intensifier, with monitors showing the x-ray images visible in background.

A depth gauge is slid over this wire to gauge the length of the lag screw. The triple reamer is used on the cordless drill which enlarges the hole within the bone to allow accommodation of the lag screw and plate. A hammer is used to tap the plate down onto the shaft of the femur. A reduction forceps may be used to appose the plate and the shaft of the femur, if the angle of the screw is slightly mismatched to that of the femur and plate. The drill is used again to drill the bone of the femoral shaft for fixation through the holes in the plate.

Following drilling the screw holes for holding the plate against the femur, a different depth gauge is used to assess the length of the screws. This depth gauge relies on hooking the distal cortex with a hook, and then sliding a barrel to the near cortex. Screws are then placed using a screw driver or the cordless drill. Finally the fascia lata is closed with sutures, as is the skin. In addition a drain may need to be placed.

The demands on a haptic-capable simulator can be expressed in a Table 2.1.

Step	Stage	Instrument	Input	Type of feedback	Force required	Area
1	Reduce Fracture	Levers/Screws	Hand	Torque	Large	Metres
2	Palpation	Hand /glove	Hand	Subtle elevation	Medium	Half metre
3	Marking	Pen	Stylus	Subtle elevation	Small	Half metre
4	Prepping	Closed clamp	Stylus	texture	Small	Half metre
5	Incision	Scalpel	Complex stylus	Constrained along axis of cut	Medium	Foot
6	Spread of tissue	Hand	Hand	Lateral resistance	Medium	Foot
7	Skin edge retraction	Self retainer	Scissor like	Spreading resistance	Medium	Foot
8	Blunt /Sharp dissection	Scissors	Scissor like	Spreading, squeezing	Medium	Foot
9	Muscle clearing	Periosteal elevator	Complex stylus	Constrained on path	Medium/Large	Foot
10	Guide drill	Cordless drill	Complex stylus	Constrained on path, and torque output	Medium/Large	Foot
11	Depth gauge	Depth gauge	Complex stylus	Constrained on path	Medium	Foot
12	Triple Reamer	Cordless Drill	Complex stylus	Constrained on path and torque output	Medium /Large	Foot
13	Lag Screw	Screwdriver	Complex stylus	Constrained on path and torque output	Large	Foot
14	Hammer	Hammer	Handle	Point force	Very large	Half-metre
15	Reduction forceps	Bone reduction forceps	Squeeze	Point and squeeze force	Medium/Large	Foot
16	Drill holes	Cordless drill	Complex stylus	Constrained on path and torque output	Medium /large	Foot
17	Depth gauge	Depth gauge	Complex stylus	Constrained on path, plunger with hook	Small	Foot
18	Fill holes	Screw driver	Complex stylus	Constrained on path, torque output	Medium	Foot
19	Suturing	Needle holder	Scissor	Squeeze	Small	Foot
20	Suturing	Forceps	Forceps	Squeeze	Small /Medium	Foot
21	Drain	Drain needle	Stylus	Constrained on path	Medium	Foot

TABLE 2.1: Demands of a haptic-capable simulator for hip surgery.

As can be seen in the above description, in order to match the characteristics of the tools which a surgeon uses in the surgery, a very complex system of haptic devices would be needed. If the simulator is not able to match all of these tools a compromise needs to be reached, such that some steps of the procedure do not have haptic input. Then an appropriate method of input must be used. This may break down the surgeon's feeling of immersion within the simulation, or require them to use a tool in a non standard way.

Using the depth gauge to calculate the length of cortical screw required to hold the plate against the femoral shaft is another complex part. This requires the simulator to enable a hook to pass through the distal cortex, and then be withdrawn until the hook catches on the distal bony cortex, after which a sliding barrel advances to the near cortex and the measurement is made.

2.2.6.2 Fidelity of the Model

The fidelity of the underlying model has a large part to play in the trainee's satisfaction with the simulator experience. The human hand has incredible resolution even able to tell subtle differences such as whether a swelling is fluid-filled or whether it is solid. Some of the key components which a haptic model requires would include physical properties for each of the anatomical components, variations in bone and changes in the properties after repeated drilling.

There are differences in the material properties of skin, subcutaneous fat, fascia lata, and muscle. Of these tissue components, fascia lata and muscle exhibit anisotropy (have different properties dependent on the direction of the force). Thus fascia lata will split easily if tensioned in the antero-lateral plane, but is remarkably resistant to failure when force is applied longitudinally. The bone needs to incorporate both cortical and cancellous components, and in addition, as trainees make misplaced drill-holes in the femur, the guide-wire tends to follow the previous misplaced drill-hole. This is a key aspect of the procedure and a source of frustration. The less the number of misplaced drill-holes the smoother the operation proceeds. In addition the instruments become harder to hold if they become covered in blood.

2.2.6.3 Stereoscopic vision

The ability to visualise a scene in 3 dimensions is critical to the trainee being immersed in a simulation. In the case of virtual reality the image seen by the trainee is essentially a flat image. Consequently it is not possible to use the eyes method of convergence, whereby the distance of the object from the eye is determined by how inward (or converged) the gaze must be in order to focus both eyes on the object. Thus for virtual reality it is only possible to create the illusion of 3 dimensions. There are several methods available for creating this illusion. These are as follows.

Firstly the size principle, whereby objects further from the viewer are smaller in size and hence project as a smaller arc on the retina (FIGURE 2.8).

FIGURE 2.8: Three virtual femurs with mid-shaft and femoral neck fractures illustrating the principle whereby objects which are smaller appear further away.

Second is obscuring, whereby objects further from the viewer get obscured by objects closer to the viewer (FIGURE 2.9).

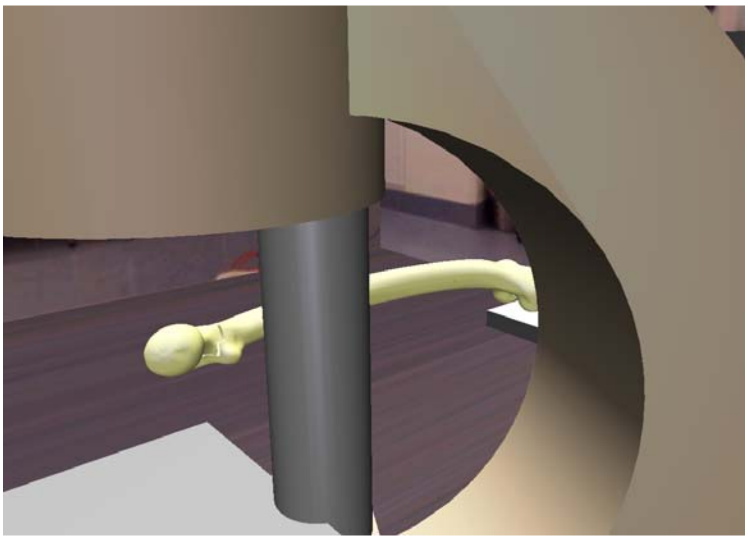

FIGURE 2.9: A view from the simulator showing the virtual femur obscured by the post from the traction table illustrating how overlapping objects give an illusion of depth.

Third is blurring of objects out of the focal plane of the eye, termed depth of field. This is often used in macro photography where a shallow depth of field emphasizes the relative distances of objects (FIGURE 2.10)

FIGURE 2.10: A photograph taken with a large aperture illustrating how blurring the background increases the illusion of depth.

Fourth is movement, which will enhance the obscuring of objects. This could be either movement of the trainee, or movement of an object in the scene (FIGURE 2.11).

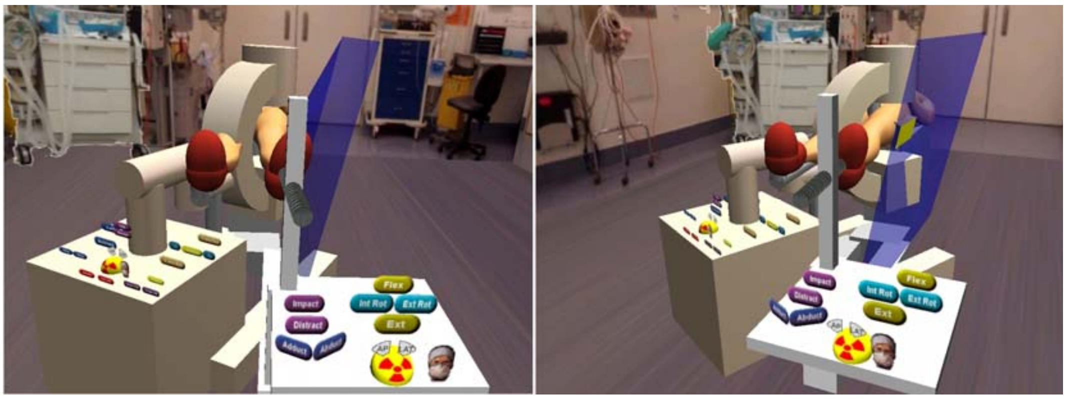

FIGURE 2.11: Two views from the simulator illustrating how movement of the viewpoint allows different objects to overlap others within a scene.

Fifth is provision of a different image for the left and right eyes. The brain identifies those parts which are obscured to differing amounts in each of the eyes and hence draws conclusions on depth (FIGURE 2.12).

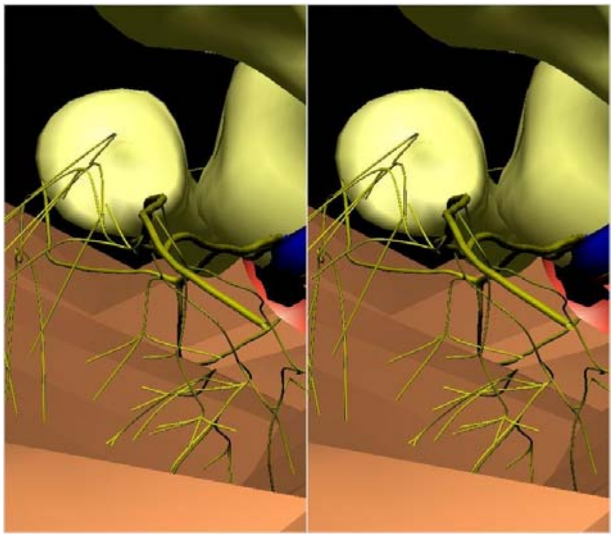

FIGURE 2.12: A virtual model of the sciatic nerve rendered as left and right eye images, showing subtle differences in overlapping of structures.

Although somewhat interconnected we will look at each of these and how they can be utilised in virtual reality simulation. The size principle is readily available for use, and through techniques such as ray-tracing, graphics cards are capable of calculating the relative distance to the viewer and of adjusting the size of the image drawn accordingly.

Obscuring is again immediately available within simulation, whereby similar ray tracing is used to identify which objects to draw and which objects will be covered. Depending on the software implementation, this layering (or z spacing) may need explicit definition. This is especially true if objects are translucent (FIGURE 2.13).

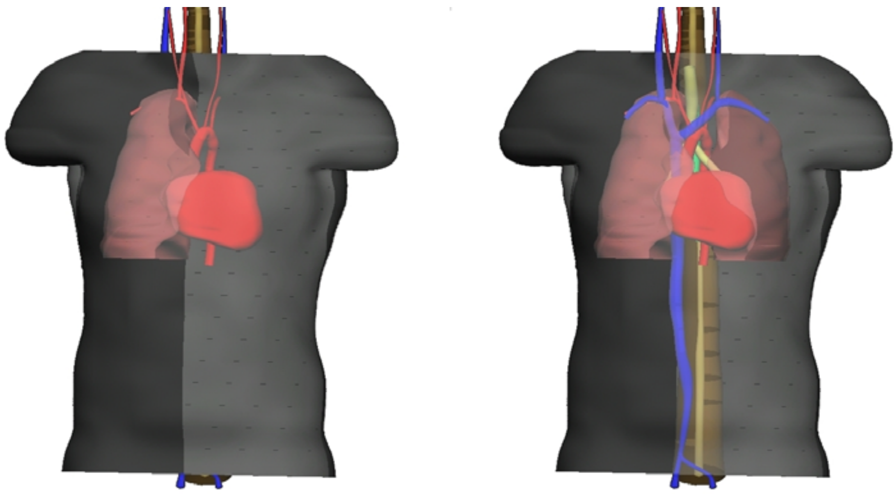

FIGURE 2.13: A virtual torso rendered a) without and b) with the order of the objects specified correctly allowing visualisation of the vessels.

Adjusting the depth of field is not currently available within most virtual reality worlds. This is because in a similar manner to convergence the eye is able to focus on different parts of the scene at will. To recreate this in virtual reality the software would need to identify which exact part of the scene is being focused on and adjust the focus accordingly. Together with the complexities of identifying this point is the speed and accuracy with which the eye settles on points. A possible implementation is the use of a "fog" type node which obscures some detail (FIGURE 2.14), but this is not really suitable for surgical simulation.

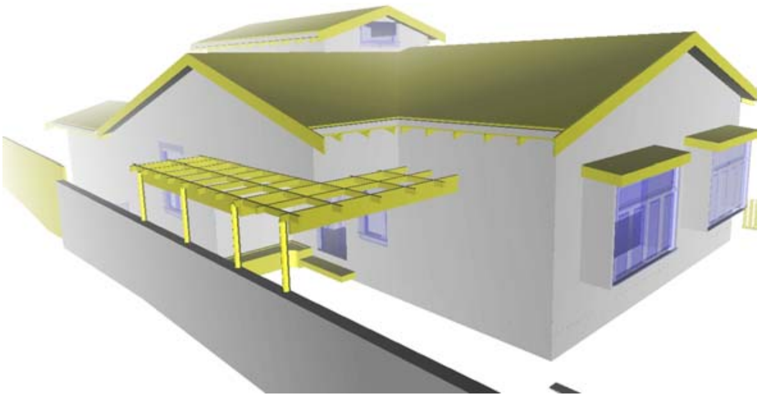

FIGURE 2.14: A virtual scene of a house showing how the use of fog can create a sense of depth.

Movement can occur in three ways, all of which will alter which objects are obscured. Firstly if the position of the head in space can be tracked, this can be used to update the scene such that you can look around an object. Secondly if it is not possible to track the head it is still possible to rotate the scene, with a mouse for example, and the viewer gets a virtual fly through of the world. Thirdly objects within the world can be moved and hence obscure other objects. Obviously it is possible to do each of these. A critical factor is insuring that there is always concordance between head movement and the visual scene presented, otherwise motion sickness can easily occur.

To enable stereo vision, two visual outputs are required, one for each eye. These outputs are then viewed either on separate monitors or Head Mounted Displays or a single monitor with either time interlacing or polarising. If the device utilises time interlacing then LCD shutter glasses must be worn. This works by outputting the right eye image while the LCD glass shuts off the left eye, and vice versa. Both polarising and LCD glasses suffer from problems of decreased luminescence of the final image. Head mounted displays currently suffer from problems such a low resolution or high weight. Resolutions which glasses are capable of rendering are around 800x600pixels. Excessive weight may cause fatigue when used for extended periods of time. In addition, not being able to see the real world can induce motion sickness in some individuals.

FIGURE 2.15: The 5DT HMD 800 head mounted display and LCD shutter-glasses.
Accessed at http://www.5dt.com

Another option which is relatively low-cost is providing two images side by side, this can be used without glasses, but requires the trainee to adjust their eyes to achieve convergence of the images, an example of this is FIGURE 2.12. This requirement for convergence can cause eyestrain. It is possible to use a system of mirrors or prisms to overcome this need for convergence, but these must be individualised to each trainee, as an individual's inter-papillary distance can interfere with their experience.

2.2.6.4 Co-Location of Haptic Device and Display

To enable hand-eye coordination the physical position of the haptic instrument must be co-located with the position of instrument as viewed by the user. In addition there is the requirement for stereovision. Graphics cards currently have the capability of supplying large resolution images in stereo.

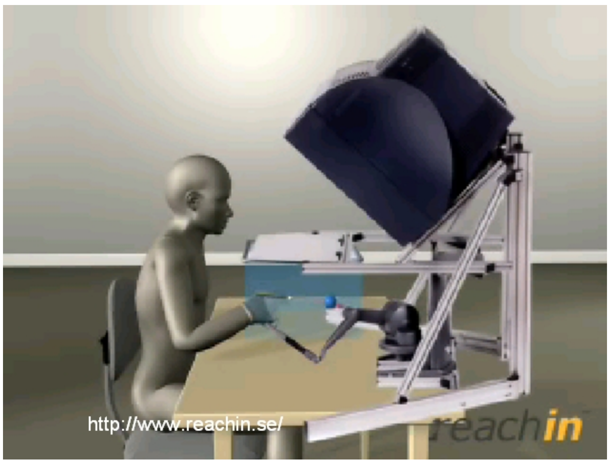

FIGURE 2.16: Co-location of image with haptic device. Accessed at http://www.reachin.se.

2.2.6.5 Ease of Setup and Cost

Although not usually taken into account in research, the ease of setup and cost of the setup is paramount to the success of the simulator. If the setup of the simulator demands a technical expert or assistant, then the costs escalate dramatically. Most simulation centres operate under a funding model, whereby they are given significant monies to setup, however very little money is given for ongoing operational budget. The cost of devices such as the Phantom Omni is currently in the order of $4,000 for a basic haptic device with 6 degrees of freedom for sensing, and 3 degrees of freedom for force feedback. The working volume of this device is movement about the elbow.

The Novint Falcon (Novint Technologies, Inc. Albuquerque, New Mexico) was released in late 2007. This retails for around NZ$300, and may provide a cost effective means to include haptics in an application (FIGURE 2.17). The Falcon has a considerable smaller operating volume, which corresponds to movement about the wrist.

Another aspect is the robustness of the device, as equipment used within simulation centres is often broken by 'enthusiastic trainees'.

FIGURE 2.17: The Novint Falcon haptic device.
Accessed at http://home.novint.com

2.3 Real world problem

This section will discuss the difficulties within the real world which virtual reality simulation can address. These include those aspects related to selection of trainees, those related to the trainees themselves, those related to the operation environment, as well as those related to the patient and their disease.

2.3.1 Trainee selection

The selection of trainee's into an orthopaedic programme is fraught with difficulty. Domains which should be taken into account include patient care, surgical skills, medical knowledge, communication skills, ethics and professionalism. In a survey of orthopaedic program directors (109 of 156 directors responded to questionnaire) Bernstein et al(Bernstein, Jazrawi, Elbeshbeshy, DellaValle, & Zuckerman, 2002) found only 5% used manual skills testing as part of their selection criteria. Earlier studies found that 1 in 6 residents selected were inappropriate, and 1 in 12 cases a serious mistake in selection was made. This is thought to be because the criteria for selection are weighted towards knowledge, rather than the other domains (Evarts CM, Kelly P, Smith RJ, Thompson RC, Cooper RR, Wilson FC, Kopta JA, Hartman JT. Report by Steering Committee on Resident Selection, 1984. Unpublished report.) in Simon (Simon, 2001). Within Simon's address as President of the American Orthopaedic Association, there is a single mention of surgical / technical skills. Indeed a very important part in patient care is deciding on the appropriate procedure. However equally important is the ability to carry out that procedure well. It is relatively easy to assess trainees on their diagnostic skills, and this is done within training weekends, however the assessment of technical skill is performed by applicant's referees. Recently further attempts have been made to make the selection process within New Zealand more transparent and more exact, utilising such aspects as referee reports, research publication and a structured interview station. However the ranking of any of these criteria is by no means an exact science. Papers like that by Thordarson et al (Thordarson, Ebramzadeh, Sangiorgio, Schnall, & Patzakis, 2007) show that there is little correlation between rankings by selection committee members at initial interview compared with final year ratings.

2.3.2 Virtual Reality Assessment of Technical Skill

Currently assessment of trainees remains largely focused on knowledge. The system relies on referee reports to identify those trainees who may need further training in technical aspects. Although this is valid, in some ways there is always the potential for the relationship between consultant surgeon and the trainee to influence behaviour. Additional aspects which further cloud this evaluation are that it may be difficult for the surgeon to allow the trainee to struggle or make mistakes (due to concern for patient welfare), and the manner in which trainees perform is different. Within surgery there are very few universally followed protocols for procedures, whereas in the aviation industry, these protocols exist such that examining pilots can predict the behaviour of other pilots.

Within the real world it is tempting to assess individual surgeon's performance. However any surgical result is determined by the overall system of care, and there are many components beyond the control of the surgeon. There is evidence to say that surgeons may perform differently depending on the hospital environment in which they work (Huckman & Pisano, 2006). Patient factors are immensely important in the outcome of a particular procedure, and issues such as compliance with the post operative protocols can make a monumental difference to their outcomes.

In order to objectively assess trainees, several criteria must be met. These include ensuring that the objectives used have intra-observer as well as inter-observer reproducibility. Inter-observer reproducibility means that the same performance would be scored similarly by different observers. Proving this reproducibility however is difficult, as having multiple observers in a live procedure will affect the trainees' performance. The alternative is to record the performance in some fashion. Intra-observer reproducibility (the same observer will arrive at the same score for a given performance) again can only be tested by recording the procedure. In both of these situations recording will narrow down the available information available to the reviewer. An example of this would be simply relying on the post-operative x-rays. This however does not provide information on how trainees get to this end-point. Training of these observers is important to ensure reproducibility. This training may be hard to achieve if these observers are busy surgeons who are providing the assessment voluntarily.

Within VR, assessment is relatively easier to achieve, as it is possible to run a series of trainees through the procedure and analyse their scores. As there is no human observer making the assessment, the VR simulator will always score equivalent performance identically, and there is no requirement for inter-observer reproducibility. The simulator can score thousands of performances.

2.3.2.1 Used to train for the task

A vital underlying philosophy of a simulator's design is similar to the Hippocratic Oath, "primum non nocere". That is, it is absolutely critical that if a simulator is used for training rather than purely assessment no unsafe methods are taught by the simulator. Currently there is no FDA requirement that simulators need to be tested to prove that they are not putting patients at risk, but simulator design needs to incorporate this underlying philosophy. The importance of the relationship between surgeon/experts and the developers cannot be stressed enough.

A cautionary example of how important it is for simulators to impart valid skills comes from the aviation industry. American Airlines flight 587 took off on 12 November 2001 from John F Kennedy airport in New York and the plane hit turbulence from a Japan Airlines plane which had taken off shortly before. As the plane hit the turbulence the pilot sensed the plane losing control and he invoked the procedure which he had been taught during his flight simulator training. This procedure advised depressing the rudder pedals alternatively, which retrospectively is suitable for manoeuvring speeds however the plane was at full power. The effect of his action was that the bolts which hold the vertical stabiliser sheared, and the vertical stabiliser became detached. It is impossible to control a plane without a tail, and the plane crashed into the suburb Queens with the loss of 285 lives. As a result of the crash investigation, this module of the simulator training has been corrected.

2.3.2.2 Introduction of decision making

A key aspect of assessing trainees is in the area of decision-making, however this is not an easily achievable task. Clinical safety relies on knowledge but also on eliciting and interpreting symptoms and signs in order to make the correct decision. The clinical environment is cloaked in ambiguity. There are so many diverse aspects that must be taken into account, that even drawing up simple clinical guidelines is fraught with difficulty. An example of this difficulty in drawing up guidelines can be found in the area of pre-anaesthetic investigations, where the American Society of Anaesthetists published a statement saying,

"*No routine laboratory or diagnostic screening is necessary*" however "*individual anaesthesiologists should order test(s) when, in their judgement, the results may influence decisions regarding risks and management of the anaesthesia and surgery*". (American_Society_of_Anaesthetists, 2003)

Diverse aspects which can affect the appropriate course of action include anatomical variation, the impact of co-morbidities(co-existing illnesses), the physiological / nutritional state, smoking status, previous surgery, social aspects, effects of medications, the exact nature of the presenting problem, including skin and soft tissue damage as well as the underlying bony problem. The introduction of the standardised patient, most commonly an actor, allows some comparison between trainees. However this method is usually suitable only for communication skills testing, and there will be some discrepancies dependant on the relationship between the surrogate patient and the trainee(Hawkins et al., 2004). VR simulation allows further standardisation of this, and is more suited to technical skills testing.

2.3.2.3 External environmental influences

There are also a multitude of external environmental variables which influence the outcome of the procedure, these include such things as the frequency of interruptions to the task (such as when the pager rings), the number of acutely unwell patients the trainee is looking after, and the impact of the supporting systems. Examples of failures within these supporting systems include instruments not being available in the set, mechanical failure of the image intensifier, or a lack of staff within the theatre.

The impact of these external influences means that it may be very hard for surgeons to objectively provide assessment for a particular trainee within any given clinical situation.

2.3.2.4 Competency

One of the key duties which a medical practitioner is obliged to perform is to recognise and work within the limits of their competence (Medical Council of New Zealand, 2004). Within the training environment this is somewhat more challenging, as trainees are frequently working at the cusp of this competence as their surgical and diagnostic skills develop. In addition surgeons who are providing oversight of the trainees' work are charged with the responsibility of identifying this level of competence to ensure that they do not work outside this limit. This is a challenging task for both trainee and surgeon.

Surgical competence is dependant on skill, experience, and knowledge. Of these identifying and assessing levels of knowledge has been well described, however the interplay and separation of skill and experience is somewhat more elusive.

2.3.3 Skill vs. Experience

Are masters of a craft born or made, and if they are born to what extent does practice impact on performance? If lesser able trainees are given coaching can they improve to a master level? The goal of training programmes should be to identify technical expertise and then provide safe methods of up-skilling in this arena, with appropriate feedback.

There are counterbalanced aspects. Masters versus Expert versus Novice describes the level of experience. Then there is Skilled versus Unskilled describing the ability to perform a task. Finally there is the capability of the test to measure or discriminate between each of these.

Many psychological experiments have sought to answer the question as to whether experts are made or born. These include the Laszlo Polgar experiment in which he home-schooled his 3 daughters in chess and produced 2 grandmasters and an international master (Ross, 2006). However the extent to which these daughters had underlying talent cannot be proven. Suffice it to say however that success builds on success, such that the motivation to practice increases as the rewards increase.

Many exponents of an art, whether chess-players, mathematicians or sports-people, use competition and the joy of victory as motivators. Having spent time on the orthopaedic training weekend, and seeing the football skills and general competitive nature displayed by the trainees it would appear that they are a group which thrive on such inducement.

2.3.4 Training within health system

The most common operative procedure to treat a femoral neck fracture is closed reduction and internal fixation with a dynamic hip screw and plate. Fixation of a femoral neck fracture is one of the first operations that an orthopaedic surgical trainee will perform. It is also often the first procedure in which the trainee uses two-dimensional x-ray images to guide correct three-dimensional placement of implants into bone. Training to perform this procedure currently occurs either in “Dry Bone” workshops, or in the operating theatre under either direct or indirect supervision by a more experienced surgeon. Dry bone workshops are relatively infrequent and, in practice, most learning is carried out directly in the operating theatre. At some point on the learning curve the trainee decides he or she is qualified to perform the procedure solo, based on their confidence and estimation of their skill. Leopold et al (Leopold et al., 2005) found males and doctors disproportionately overestimated their skill both before and after training. This finding worsened as they became more confident.

Most learning sessions for trainees rely on a more traditional model of education, whereby the trainee travels to a surgical skills training centre, and devotes an intensive period of time to a particular task. Teaching sessions with current surgical simulators often follow this model because the simulator in use relies on specific and often expensive hardware, or software that requires specialized installation. As a result, these types of simulators remain located within simulation/training centres, and may rely on simulation personnel for guidance. As well, there is evidence that, although trainees may hone their skills in a specific area during a skills training course, there is a consistent decline in knowledge over time (J. Ali et al., 2001).

2.3.5 Reduction in Work Hours

The traditional apprenticeship style of training is/was thought to require trainees to work long hours. Prior to New Zealand junior doctors going on strike in 1984, hospital boards actually paid junior doctors less wages per hour if they worked overtime. Thus there was a financial incentive on behalf of the health boards to under-staff the hospital and as a result the experience gained by junior doctors was significant. This strike introduced to New Zealand the concept that no doctor should work more than 144 hours in a two week timeframe. This model works well for those jobs which require the doctor to be on-site. As the doctors advance in their training, the requirement to be onsite diminishes, and the doctor can remain on-call, and need only attend the hospital to resolve more complex issues, or operate. The varied workload while on-call means that in order to make the roster 'legal' an excess number of registrars are required to be employed. This increase in doctors means that the experience gained within the operating theatre is diluted, and trainees are taking longer to complete a similar number of cases.

The role of fatigue has now been realized and as a result, these long hours are no longer acceptable. In 1999, the Federal Council of the Australian Medical Association adopted a National Code of Practice regulating the hours of work, shift work, and rostering for hospital doctors (Australian Medical Association, 1999). The New Zealand District Health Board Multi-Employer Collective Agreement has also stipulated limitations in the number of hours worked per week by surgical trainees in New Zealand (New Zealand Residents Doctors Association, 2002). American studies have shown that reduction in resident work hours leads to a better quality of life and improved scores by surgical residents in examinations assessing basic surgical education (Barden, Specht, McCarter, Daly, & Fahey, 2002). However, it is not certain how limitations on working hours for surgical trainees impacts on the acquisition of technical skills (Barden et al., 2002). Trainees believe that the reduction in hours may lead to adverse outcomes in patient care and ability to acquire operative skills (Whang et al., 2003). In addition, the decreasing hours worked by trainees potentially reduces the amount of time available for learning from complex problems that evolve over weeks (Silen, 2003). Options to address these perceived problems include either extending the training period or changing the method of surgical training. Surgical simulation provides one method for achieving this task (Kneebone, 2003) .

The demands of a surgical career on family life are significant. There is also an indication that attitudes amongst trainees are changing, with greater focus on family life, rather than surgical career

(Lind & Cendan, 2003). The number of unfilled general surgery programs in the US went from 5 in 1997 to 41 in 2001 (Gelfand, Podnos, Wilson, Cooke, & Williams, 2002). A recent survey looking at surgical inclination was conducted on Auckland University medical students (Insull, Kejriwal, Segar, & Blyth, 2006). 56% of these students felt lifestyle was a factor in career choice. Of those who were non-surgically inclined 94% felt lifestyle was important, while only 23% of those who were surgically inclined agreed with the statement. This suggests that prospective trainees may be less likely to pursue surgical training because of the impact on lifestyle. Surgical workshops which require trainees to give up their weekends are less likely to be attractive than training which can be done on the job.

2.4 Validation of Simulators

This section describes how simulators can be assessed. The assessment of simulators is important if the community is to spend time and money on a simulator, especially as involvement with a simulator may change the culture of the training community.

Flight simulators underwent little or no formal validation during their development. Indeed if there had been studies on the earliest simulators, the results would be interesting to review. However medical simulation exists in an era where there is a tendency to measure and critically analyse as much as possible. Validation of a simulator is important, however equally important is to identify whether the areas where a simulator might be found lacking are important clinically, or whether despite its failings it still has a valid purpose. In a similar manner if the only tool in the toolkit is a large adjustable wrench, nails can still adequately be driven into a plank of wood, until someone arrives with a hammer.

There are a number of ways a simulator may be validated. Simulation is in its infancy, and as a result descriptions of these different forms of validation are not entirely consistent.

2.4.1 Content related validation

This is a test of whether a simulator measures the skill it actually intends to measure. That is how well the subject matter of the simulator and the subject matter of the real world example coincide. An example could be "Is observing peeling an orange a valid way of testing ability to perform soft tissue dissection well?"

Content related validation can be subdivided further based on who is validating the simulator.

2.4.1.1 Content validation

Content Validation is performed by a panel of experts in the subject field, whereby experts in the field examine the simulator and ascribe how well the simulator examines the skills which the simulator sets out to examine. This might be influenced by the amount of experience the user has with the simulator interface, and potentially their own bias towards simulation.

2.4.1.2 Face validation

This is assumed to be non-experts judging the simulator on how closely it resembles a facsimile of the real operation, however it is unclear how exactly this is judged, unlike the Turing test, or whether the definition of expert relies on their knowledge in the field of validation, or someone with local knowledge of the environment. This will be discussed further in Section 4.4.

2.4.2 Criterion related validation

Similar to inter-observer reliability, this validation method tests whether a simulator scores a user similarly to another independent measure of the same skill. Within surgery this validation exercise is difficult to perform, as there are very few independent measures of skill. Usually a comparison with a standard bench type training exercise is used. This becomes more difficult as the simulation task becomes more complex. Work by Fried et al (Fried et al., 2004) showed that scores on a laparoscopic simulator were predictive of intra-operative performance.

2.4.3 Construct related validation

This group of tests determine whether a simulator matches the particular educational construct which is set up. An example would be the construct that trainees with increasing levels of expertise should perform better on the simulator. Thus the simulator could discriminate whether a particular trainee's performance is equivalent to a real-world master, or whether they are mediocre. The difficulty with this type of validation is ensuring that the construct is appropriate. As in real surgery there are a number of potential confounders. Within the example of increasing levels of expertise, there needs to be an identifiable method of testing these levels. A simpler (but worthless) construct might be "Do surgeons perform better when not blindfolded". It would be relatively simple to test this premise, prove that surgeons perform better when not blindfolded, thereby validating the construct, but not really proving anything about the value of the simulator. Thus the construct chosen must be carefully crafted in order to obtain meaningful results, while still being simple enough that confounders do not interfere excessively. This will be discussed further in Chapter 5.

2.4.4 Transfer validation

Transfer validation tests whether skills learnt on a simulator transfer to improved real world performance. This is perhaps the most important validation for a simulator, as it shows the applicability of the simulator to the real-world problem of performance. The criteria used to test performance on the simulator and real-world performance need to be carefully selected. Potential issues include the impact that conducting the test has on the results, i.e. the trainees might be place more emphasis on the task, due to the simulator exercise, and their performance will improve. In that way even if a simulator in itself does not improve performance, enrolling in the study may contribute positively, as may a simpler simulator. The development of laparoscopic virtual simulators has demonstrated that at least some technical skills can be transferred from the virtual environment to the operating room.(Grantcharov et al., 2004; Hyltander, Liljegren, Rhodin, & Lonroth, 2002; Scott et al., 2000; Seymour et al., 2002)

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2.5 Choice of programming language/interface

This next section describes the programming environments which could be used to develop a simulator. Rather than describing all of the available options for language, of which there are an increasing plethora, the focus will be placed on the programming language which was selected, and more specifically on the range of plug-ins which are available within Virtual Reality Mark-up Language (VRML).

The question of which programming language should be used is perhaps the most commonly asked question concerning development of a simulator. There exists no perfect language in which to program. Each has its own foibles and fortes. The advantages of an older language include adoption by a number of groups, an ability to work on older computers, and perhaps robustness. The advantages of a newer language include cutting edge technology, (but with the probability of bugs), and dependencies on faster, more capable hardware. The fact that as at 2007, almost all computerised systems within aircraft run on x286 computers is a testimony to the fact that old does not necessarily mean redundant (personal communication -Bob Henderson).

The main criteria used to select a language for developing the simulator were ability to run on the older style computers found within the hospital environment, ability to display realistic images of the virtual scene in real or near real time, the ability to use a standard interface to ensure trainees did not have to learn new skills to use the simulator, robustness in installation, open source rather than a proprietary format, the ability to integrate with a web-browser for uploading of data to a web-server, and finally ease of coding. In this regard Virtual Reality Mark-up Language was selected.

The Adobe Acrobat Reader v8.0 package has become 3D capable, and VRML objects can be embedded within .pdf documents, allowing users to rotate a 3D object without any further download. This will allow the creation of 3d "printouts" or more specifically downloads for trainees to review their previous performances on the simulator.

Virtual Reality Mark-up Language is based on a project started at Silicon Graphics Inc. by Rikk Carey and Paul Strauss. This project's focus was to design and build the infrastructure for interactive 3D graphics applications, the outcome was called Open Inventor. Gavin Bell then used the reference manual from this to create the first draft of VRML 1.0 specification. This specification was published in October 1994 at the Second International Conference on the World Wide Web in Chicago. VRML 1.0 allowed for the creation of static worlds with support for shape building, lighting and textures but with very little interaction, except hyperlinks to other resources, such as HTML or MIME types. It was a successful 3D file interchange format, allowing import and export of 3D geometry between software applications.

The lack of features such as animation, interaction and behaviour drove the development of the VRML 2.0 specification. This was subsequently improved with the ratification of VRML97 by ISO in December 1997. Subsequently this has been superseded by X3D, which is an xml based format. X3D and previously VRML forms the basis for MPEG4 part 11, which describes the 2 or 3D composition of audiovisual content allowing animation and interaction. Browsers are continuing to be developed utilising X3D and due to ability of VRML to act as a file interchange format, these browsers are backwards compatible.

The basic structure of a VRML file is a series of nodes and routes. The nodes comprise either transformations, geometries or scripts. The routes coordinate interaction between either the user and these nodes or between the nodes themselves.

Features of VRML are the scene graph structure, sensors and scripts, interpolators, event architecture, and prototyping.

A hierarchical scene graph structure facilitates control of nodes. By nesting nodes within others it is possible to simplify the coding governing action. For example with a series of nested transformations, changing a rotation higher up the hierarchy causes nodes below it to be changed. An analogy would be flexion of the elbow causes a rotation of the forearm as well as hand and fingers.

Sensors are nodes which allow the user to interact with the virtual world. These range from simple touchsensors, to more complex sensors which calculate the amount of rotation the user is specifying based on their mouse strokes.

Interpolators provide a simple means to specify fractions which can be used to drive animations or positions.

Script nodes provide the power behind the logic within VRML. Complex behaviours or algorithms can be modelled using either JavaScript or java. Data from either the user or interpolators can be manipulated and then used as the input for other nodes.

Event architecture provides the mechanism by which information is passed from node to node. Within VRML this is provided by ROUTES. Thus the output from a script node can be passed via a ROUTE to another node to provide animation and interaction.

2.5.1 Use of external prototypes

Prototyping allows nodes to be described once and then reused a multiple of times. This allows ease of encoding as well as reduction in VRML file size. In addition the ability to specify these prototypes external to the file allows these prototypes to be placed anywhere on the internet.

2.5.2 VRML browsers

There are a number of VRML browsers available for download. The extent to which they are compatible with the VRML specification is variable, as is the ease of use of the interface.

2.5.2.1 Cosmoplayer

Cosmoplayer was developed in the late 1990s and was developed from a number of companies including Cosmo software, SGI, Platinum and Computer Associates. It had a very intuitive navigation interface and required a small amount of memory to run. It utilized either OpenGL or DirectX libraries, or could run entirely using software for machines without graphics hardware. Unfortunately in around April 2006 Microsoft released a security patch KB912812. This changed the way internet explorer dealt with ActiveX controls. Relevant articles concerning this patch are

- http://support.microsoft.com/kb/912812

- http://support.microsoft.com/kb/912945

- http://support.microsoft.com/kb/917425

The patch meant that Cosmoplayer could no longer be used with internet explorer. The fact that Cosmoplayer is no longer supported by any company means that no work-around has been developed. Cosmoplayer can work with Firefox, however the installation is somewhat technical, and for this reason it was elected that another web browser would be needed as requiring users to install a different web browser would prove a barrier to uptake of the simulator.

2.5.2.2 OctagaPlayer

OctagaPlayer (www.octaga.com) is a 3d browser which supports both X3D and VRML formats. It continues to be developed by Octaga AS (Gullhaugveien 11, NO-0484 Oslo, Norway). It has a free VRML browser which can either be used within a web browser or as a standalone application. Octaga also has multi-user server applications and modellers for commercial applications. There are plug-ins available for windows, Linux and Mac OS X. The navigation is fairly intuitive though not quite as intuitive as Cosmoplayer. Due to its ongoing development, available support and signed Active X controls it was selected for the development of the Bon*e*doc simulator.

2.5.2.3 Flux

Flux (www.mediamachines.com) is developed by Media Machines Inc, located in the USA. The CFO is Tony Parisi, who has been intimately involved with VRML since the beginning. It also has Flux studio, which is a GUI interface for model creation. Both of these are freeware for private and academic use. Navigation, load and running speed of the Bon*e*doc simulator are not as easy or as fast as OctagaPlayer.

2.5.2.4 Xj3D

Xj3D (www.xj3d.org) is a toolkit for VRML97 and X3D written in Java, and developed by the Web3D Consortium. At present it does not have enough conformance to those parts of the specification utilised by Bon*e*doc to enable its use.

2.5.2.5 Cortona

The Cortona VRML (www.parallelgraphics.com client is developed by ParrallelGraphics, with Research and Development based in Moscow, Russia. At present it does not have enough conformance to those parts of the specification utilised by Bon*e*doc to enable its use.

2.5.2.6 Blaxxun Contact

Blaxxun Contact (www.blaxxuntechnologies.com) is developed by Blaxxun Technologies, based in Munich, Germany. At present it does not have enough conformance to those parts of the specification utilised by Bon*e*doc to enable its use.

2.5.3 Communication with web browser

The ability of the VRML browser to communicate with the web browser is critical as this allows uploading of data from the simulator via the internet to a central repository. Of all the browsers Octaga has the easiest interface with html.

2.5.4 Inbuilt navigation

The ability of the VRML browsers to handle navigation within the simulator, as well as rendering via use of OpenGL or DirectX libraries has meant that the simulator development could occur at a fairly high level. The ease of programming has easily overcome the performance loss inherent within higher level programming languages due to the speed with which modern computers operate. In some ways VRML was ahead of its time, and the capabilities of the language outstripped the abilities of computers in the late 1990s such that the uptake was not as impressive as predicted.

2.6 Examples of simulators currently available

There are a number of simulators of orthopaedic simulators which are still within the research environment. These simulators are mostly arthroscopic simulators, which enables them to avoid issues such as co-locating haptic displays with the visual scene as described in Section 2.2.6.4.

The American Board of Orthopaedic Surgery provided funding to Boston Dynamics for a prototype simulator to the value of US$50 000 in 1997. This funding was based on three tenets,

> *" … first that in order for this effort to succeed it must be embraced by the entire orthopaedic community; second, that the tool must be shown to be valid and reliable; and third, that before it could be used as an adjunct to certification or recertification examinations, orthopaedic surgeons must have had ample experience with it and be confident that it is a realistic and useful surrogate for actual operative interventions." (Poss et al., 2000)*

These are indeed hard claims for any technology to match up to, as there is little likelihood the entire community will embrace any solution. This embrace will only occur when the community feels that it has been validated and is reliable, though these definitions are not absolutely defined. Obtaining enough experience on the simulator means that such a solution must be extremely cost effective for it to be used in such a widespread manner. This simulator is still under development.

The Prodecius VR Arthroscopy simulator (Mentice Corp, Göteborg, Sweden) is currently available commercially. It has both shoulder and knee modules. It incorporates either a non-haptic or haptic instrumentation. Gomoll et al (Gomoll, O'Toole, Czarnecki, & Warner, 2007), used this system in a basic training mode, requiring users with different levels of experience to navigate and touch virtual balls, showing improvements with time in the parameters such as time to complete the task, and path length of the instruments.

A simulator called Virtual Reality Arthroskopie Trainingssimulator (VRATS) has been developed by Muller et al (Muller, Bockholt, Lahmer, Voss, & Borner, 2000). There is no indication of the extent to which results are measured. The version described in the article used a box trainer type of input rather than haptics.

The United States Military's Thigh Trauma Simulator is being developed by Touch of Life Technologies (Aurora, CO, USA). This is based on the Visible Human Project® dataset (which will be discussed further in Section 4.3.1.1), and incorporates a volume dataset and physics, and utilises the Phantom® haptic device (Reinig, Lee, Rubinstein, Bagur, & Spitzer, 2006). Locking of femoral nail by placing the distal locking screw has been developed, though currently this has not been validated.

The Sheffield Knee Arthroscopy Training System (SKATS), has been developed at the University of Sheffield, (Sheffield, UK) (McCarthy, Moody, Waterworth, & Bickerstaff, 2006). This system uses passive haptics which relies on touch feedback of the arthroscopic instruments touching the physical model of the knee. The position of the instruments is tracked using the miniBIRD® electromagnetic tracking system (Ascension Technology Corporation, Burlington, VT).

Jaramaz and Eckman (Jaramaz & Eckman, 2006) report on a system to simulate fluoroscopy. The application they have reported describes how the system can be used to practice fluoroscopic navigation. This navigation requires users to identify key landmarks from an image intensifier image of a pelvis, these points are then used to create a virtual model of the pelvis suitable for guiding total hip arthroplasty. The system includes a 1/6 size dummy of both an image intensifier and a patient.

Tillander et al (Tillander, Ledin, Nordqvist, Skarman, & Wahlstrom, 2004), tested medical students and orthopaedic surgeons on a system for distal locking screws and found that although surgeons operated faster, this increased speed was only significant in the first of the three repetitions.

2.7 Summary

This chapter has presented the background and a brief description of the issues regarding simulation in orthopaedics. An understanding of the history of aircraft simulation allows insights into the path which medical simulators may take, and also an awareness of how the differences between the industries have shaped and continue to shape the uptake of simulation. Included is an awareness of factors which make simulation appealing as well as those which impede its acceptance.

Given the limited budgets which institutions have to spend on healthcare, proof must be made that each healthcare dollar is well spent. Counterbalancing this is a growing awareness amongst the public that they do not want to be the guinea pigs in healthcare training.

The second part of the chapter described the various options available for simulation, using a substitute for a patient on which to practice surgical skills. This included a description of the difference between part and entire task trainers. Irrespective of whether a simulator encompasses whole or part of a task an analysis of the attributes of the simulation method is necessary. Thus the fortes and foibles of each of the modalities of simulator were presented. This includes the modalities of cadaveric, animal, synthetic materials as well as those of virtual reality simulators.

Within virtual reality simulators there are a range of differing aspects which create a sense of immersion within a simulator. Discussion on the challenges of haptics and stereoscopic vision within a simulator was presented.

An understanding of the underlying problems within the real world offers insight into the setting in which VR simulation can be used and the options for providing resources which can not be addressed using other modalities. This includes factors related to trainee selection and credentialing, those factors inherent to the work environment of the trainees. In addition those factors which the patient or the disease brings to the problem of a successful operation were then presented.

It is not enough to create a simulator, it must be shown that the simulator is valid. As simulators are undergoing development, so is our description of what valid means, consequently a brief overview of the various forms of validation was presented to set the stage for subsequent chapters.

Finally the choice of programming language and interface was discussed, as in this area a number of possible platforms are available. The overriding philosophy was ease of installation and use for the simulator, as well as an ability to use hardware found within the hospital environment. It is of no use to a patient to have a simulator developed which the trainee who is operating on them has not used. Thus a simulator must be affordable and accessible.

Subsequent chapters will discuss all of these issues in further depth.

3 ATTITUDES TO SIMULATION

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

3.1 Introduction

A survey was conducted to assess the attitude of New Zealand orthopaedic surgeons towards simulation. The primary aim of this study was to measure the response of orthopaedic trainees and surgeons towards the potential use of virtual reality (VR) surgical simulators in orthopaedic surgical training, with a particular focus on the perceived requirements for a simulator and the tasks for which simulation would be useful. A second aspect of the study was to determine the acceptance of surgical simulation by the orthopaedic community. The hypothesis was that recent graduates and trainees would support computerized surgical simulation more strongly than more experienced surgeons. A postal survey was sent to all orthopaedic specialists and advanced trainees in New Zealand.

3.2 Methods

3.2.1 Development of survey:

A 44 item structured questionnaire was developed for this study. This questionnaire was divided into 10 sections. The questionnaire can be found in Appendix A. The main sections were demographics (including current computer usage and current revision methods); the respondent's overall view of surgical simulation; the specific requirements for a successful orthopaedic simulator; the tasks for which the end-user thought simulation might useful; and the potential utilization (including specific surgical procedures and role/s in accreditation). A five centimetre visual analogue scale was used to quantify responses from "Disagree Strongly" to "Agree Strongly'. This was measured using a digital calliper and converted to a 10 point score. The visual analogue scale allows a continuum of responses, thereby reducing the artificial distribution of positive and negative responses.(Bond & Lader, 1974) Surgeons in New Zealand are also familiar with the scale as it is used locally for prioritizing patients for elective surgery.(MacCormick, Plank, Robinson, & Parry,

2002) Free text box replies were also sought for comments about experience of previous simulators.

3.2.2 Survey administration:

218 surveys were mailed out to 190 orthopaedic surgeons and 28 advanced trainees practising in New Zealand. All responses were anonymous. A second and third mail-out was sent to those surgeons who had not responded within a month of each mail-out.

3.2.3 Statistical Analysis:

Coded survey responses were manually entered into an electronic spreadsheet. Descriptive statistics were calculated and where the data had a normal distribution, paired t-tests and ANOVAs used to test for equality of populations. Non-parametric data was analysed using either Mann-Whitney U or Kruskal-Wallis non-parametric ANOVA. Data are presented as percentages or as means + standard deviation (s.d.)

3.3 Results

3.3.1 Sample demographics:

The response rates were 96 replies to the 1st mail out, 34 replies to the 2nd mail out and 22 replies to the 3rd mail out. Ten replies were from retired surgeons with incomplete surveys and these were excluded. This gave an overall response rate for complete surveys of 68% (142/208). Of the respondents, 118 were practicing orthopaedic surgeons and 24 were trainees (TABLE 3.1). Approximately half of the respondents (73 out of 142) had gained their fellowship prior to 1990. The most common age group was 40 to 49. Internet usage was high with 56% stating that they accessed the Internet every day. A further 23% accessed the Internet twice weekly. Despite high usage of computers, more than twice as many surgeons used orthopaedic textbooks (86/142) than CD-ROMs (34/142) for revising surgical approaches and procedures. Only 7 respondents had previously used a simulator. In 3 of the 7 cases, the simulator was a flight simulator.

	Trainees	Surgeons qualified later than 1989	Surgeons qualified in 1989 or earlier	Total
Gender:				
Male	20	41	71	132
Female	3	2	2	7
Not specified	1	2	0	3
Average age (years + s.d.)	30.4 +/-3.6	34.9 +/-5.6	50.1 +/-8.4	42.6 +/-10.4
Total number of survey participants	24	45	73	142

TABLE 3.1: Demographics of respondents.

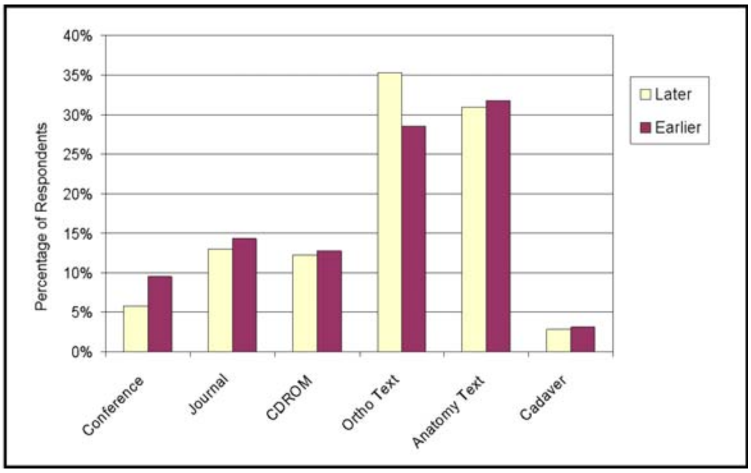

Figure 3.1: Histogram of methods used for revising surgical approaches and procedures by frequency of response.

To ascertain the effect of length of surgical experience on the responses to our survey, the responses were divided arbitrarily into two equivalent-sized groups, based on the year that the respondent had obtained their surgical Fellowship. The two groups were those who had gained their FRACS before 1990 (a total of 73 respondents, average age 50.1yrs +/-8 yrs), and those who had either gained their FRACS after 1989 or were still advanced trainees (a total of 69 respondents, average age 34.9yrs +/- 5.6 yrs). Those surgeons who had gained their orthopaedic surgical fellowship before 1990 were more likely to access the Internet daily (61% versus 51%). They were also more likely to have had experience with simulators (5/73) versus (2/69).

3.3.2 Overview of tasks and requirements for successful simulators:

All respondents agreed with the statements that use of a surgical simulator to practice orthopaedic surgical procedures would provide effective feedback to the surgeon and that this feedback would be non-threatening (TABLE 3.2). However, recently qualified surgeons had different opinions to earlier qualified surgeons as to the importance of practising in a simulated environment prior to carrying out an operative procedure. This survey question defined this practice as occurring without the possibility of endangering patient welfare. Recently qualified surgeons were much less likely than earlier qualified surgeons to agree that the opportunity to practice in a simulated environment is important (median score 5.6 versus 7.7, p=0.03).

	Surgeons qualified later than 1989	Surgeons qualified in 1989 or earlier	Group median (range)
Overall view of simulation			
•'It is important to practice in a simulated environment'	5.6	7.7 †	6.8 (0 – 10)
•'Simulation is an effective means to enhance feedback'	7.2	7.7	7.5 (1.6– 10)
•'Feedback from a simulator is non-threatening'	7.8	8.2	8.1 (2.1– 10)
Specific requirements for a surgical simulator			
•24 hour Availability	4.9	3.6	4.5 (0 –10) *
•Haptics	7.9	8.1	8.0 (0.7 – 10)
•Realistic view of operation	9.0	8.9	9.0 (4.2– 10) **
•3-D view	8.5	8.5	8.5 (0 –10)
•Different scenarios	8.8	8.1	8.5 (0 –10)
•Test problem solving ability	7.9	7.9	7.9 (1.3– 10)
Tasks for which a simulator would be useful			
•Revision of surgical anatomy prior to operation	7.2	7.5	7.2 (0 –10)
•Feedback on performance	7.6	7.7	7.6 (0 – 10)
•Pre-operative planning	7.5	8.0	7.7 (0.5 –10)
•Practice of insertion and angulation of guide-wire	8.5	8.2	8.4 (2.9– 10) ***
•Practice of minimally invasive surgery	8.1	7.7	8.0 (2.2– 10)
•Practice of open surgery	7.3	7.7	7.5 (0 – 10)
The future of simulation			
•Will impact on practice in the next 5 years	5.0	4.9	4.9 (0-10)
•Can be used for accreditation in the next 5 years	2.4	4.1 ‡	3.0 (0-10)
•`Can be used for accreditation in the next 10 years	4.5	6.0 §	5.0 (0-10) ****

TABLE 3.2: Survey responses by year of qualification.

Responses were measured on a five centimetre visual analogue scale, from strongly disagree to strongly agree and converted to a score out of ten.

* $p < 0.001$ 24 hour availability significantly less important than other requirements
** $p < 0.01$ Realism significantly more important than all other requirements
*** $p < 0.01$ Angulation significantly more important than other tasks except MIS.
**** $p < 0.0001$ Significantly more likely to be used for accreditation in ten years
† Earlier qualifying surgeons rate practice in simulated environment more highly ($p = 0.03$)
‡ Earlier qualifying surgeons rate use for accreditation in next 5 years more highly ($p = 0.04$)
§ Earlier qualifying surgeons rate use for accreditation in next 10 years more highly ($p = 0.001$)

Realism was the most important requirement, scoring a median of 9 out of 10 on the linear analogue scale. Respondents felt that a surgical simulator would be most useful to practise the insertion of a guide-wire into bone with the correct angular alignment, a task that is critical for fracture fixation and placement of orthopaedic implants. This task had a significantly higher median score than all other tasks ($p < 0.01$) except for the practice of minimally invasive surgery. Revision of surgical anatomy prior to undertaking the operative procedure was felt to be the least useful task for a simulator (median score 7.2). 24-hour availability of simulators was the least important of the six requirements listed in the survey ($p<0.001$), with a trend towards the later qualified surgeons and trainees scoring 24-hour availability higher than the earlier qualified surgeons (median score 4.9 versus 3.6 $p=0.06$).

A simulator for arthroscopy (as opposed to other procedures) was thought to be the most helpful with 76 of 135 respondents who answered the question agreeing to this statement (FIGURE 3.2). There was a statistically significant difference between the two groups as to whether a simulator for Image Intensifier guided procedures would be helpful with 43% of earlier qualifying surgeons indicating a simulator would be helpful, compared with only 19% of later qualifying surgeons($p=0.001$).

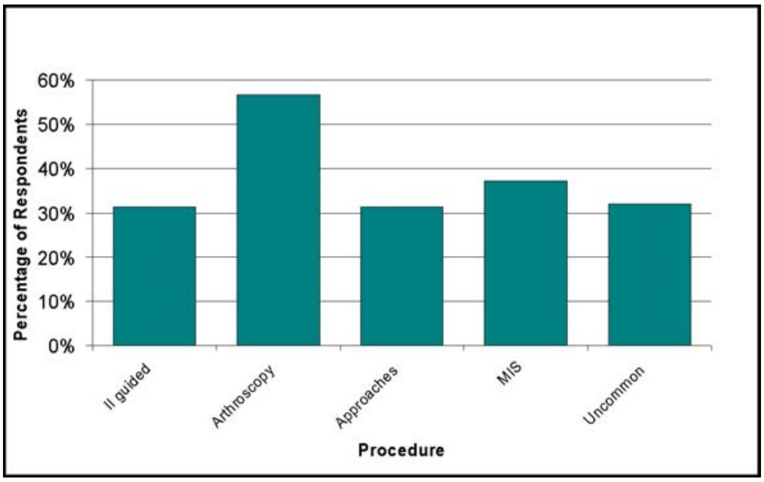

FIGURE 3.2: Histogram showing which surgical procedures respondents thought should be simulated.

3.3.3 Utilization of surgical simulation in practice and as an accreditation tool:

3.3.4

Both groups were equally divided on the question of whether surgical simulation would impact on surgical practice in the next 5 years. Respondents generally felt that surgical simulators would not be useful in the next five years for accreditation (median score 3.0 out of 10). The earlier qualifying surgeons scored the statement that VR simulation could be used for accreditation in the next 5 years significantly higher than the later qualifying surgeons (median score 4.1 vs. 2.4; p=0.04). There is greater expectation that simulation may be used for accreditation in the next 10 years, with a significantly higher overall score of 5.0 (p<0.0001). Again as can be seen on FIGURE 3.3 the earlier qualifying surgeons gave higher scores to this statement (median score 6.0 vs. 4.5; p=0.001).

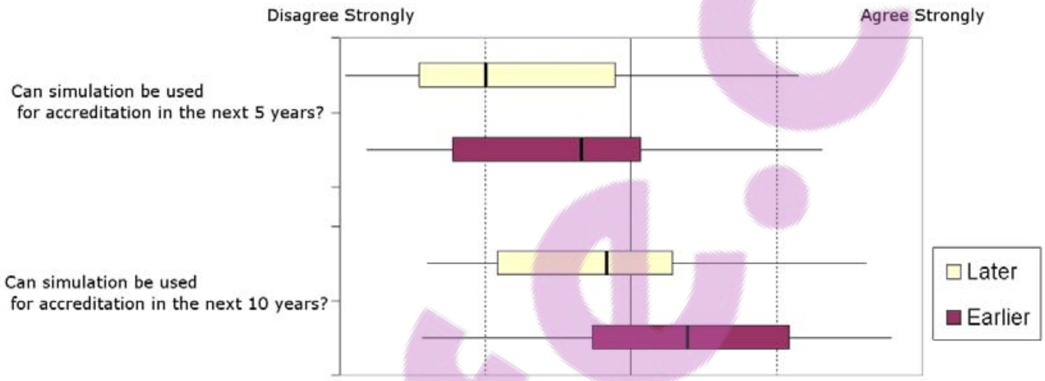

FIGURE 3.3: Box and whisker plot comparing the respondent's views on the use of simulation for accreditation.

3.4 Discussion

The purpose of this study was to assess the attitudes and beliefs of the wider orthopaedic surgical community towards surgical simulation, with particular focus on the perceived requirements for a successful simulator and the type of tasks for which a simulator would be helpful.

Only 4 respondents had practical experience with the use of a surgical simulator. However, the viewpoints of the remaining respondents were felt to be important as the beliefs of these surgeons / trainees will have significant impact upon the uptake and acceptance of simulation technology by the wider orthopaedic surgical community.

It was found that both surgeons and trainees believed that use of a surgical simulator could have useful applications in orthopaedics, in particular for the practice of arthroscopic surgery and operative techniques such as guide-wire placement and minimally invasive surgery. However, surgeons were generally not convinced that surgical simulation would have a 'real-world' impact on their own surgical practices in the next 5, or even 10 years.

The ease and speed of uptake of new technology into a community is dependant on a number of factors. Some of these factors are common to all technologies, and as such lessons from other communities and technologies can be applied. Other factors include the number and strength of drivers for acceptance of that technology as well as the barriers to uptake of this technology.

3.4.1 Introduction of New Technology

Perhaps the most important component of the success of any simulator is the attitude within the profession towards simulation as a whole, and equally towards a particular simulator. As with any technology in its infancy, there are a number of common steps. Firstly the technology is heralded. This usually takes place before the technology is proven; in a way this can be likened to science-fiction, whereby people conceptualise the schema, perhaps utilizing somewhat fabricated illustrations of how the technology will perform. An example of this heralding within the orthopaedic realm is a symposium presented within Clinical Orthopaedics and Related Research (Vol 354) 1998. The editorial written by Digioia (DiGioia, 1998) is entitled "What is computer assisted orthopaedic surgery?" This symposium sought to introduce the orthopaedic community to the various roles computers might have within surgery. These roles include pre-operative planning, navigation, augmented reality, and simulation. The status of the journal and author is important if it is to plant the seed within the community that the technology may have an important role to play in their work. The timing of this heralding event is important, and to maximise uptake of the technology the lead-in time before the actual appearance of the technology must not be too long or the community may become disillusioned. Eight years later, the journal published another symposium, specifically related to virtual reality applications. The marketing of this first example of simulation is essential. If it promises too much, then the market will see too many faults within the technology and reject it. If it promises to little, then the technology will be overlooked. The users' first experience with the technology is paramount. An example of this is the installation of a software product. If for any reason it does not install robustly, then many surgeons will not have the expertise to find the fault with the installation, and are unlikely to make further attempts to get the software to run. The number of unused CD-ROMs for promotional products within the average office testifies to the importance of fast, robust and easy installation to the success of the simulator. Users of computer based applications have increasingly high expectations of the speed and robustness of software products.

Within the simulation community, the tendency is to use state of the art technology, with the result that the development of the simulator is slowed due to the inevitable teething problems that besets new technologies. Coupled with this is the use of hardware that is developed particularly for that high-end market. Consequently when a simulator is produced, it is only available for the few that can afford it. The tenets with which the American Board of Orthopedic Surgeons funded development of a simulator include being embraced by the entire community, and surgeons having ample experience with it prior to being used in accreditation(Poss et al., 2000). Simulators which are going to satisfy these requirements will by necessity be low cost to the end user.

It is only recently that simulators have started to exit the research centres and enter training facilities. There are an increasing number of papers written about the validity of simulators, which will be discussed in a later chapter, however it behoves the simulation industry to continually focus on the needs of the surgical community. Loss of this focus may result in the creation of expensive technological solutions to problems that the surgical community does not have, thereby jeopardizing this important relationship.

A side effect of any measurement tool is that it alters the subject it is attempting to measure, such as the drop in voltage when a voltmeter is incorporated within a circuit, or change in temperature with a thermometer. In this survey the converse effect may have taken place by simply introducing the concept of simulation to surgeons; this may make them more biased towards the potential of simulation, by asking them to examine the areas within which simulation could be used, and introducing them to some of the technologies as well as means of critiquing simulators.

Currently most simulators cited in the literature simulate general surgical operations, and these are almost exclusively laparoscopic surgical procedures (Dunkin, Adrales, Apelgren, & Mellinger, 2007; Haque et al., 2006). Laparoscopic simulators have a number of objectives: firstly to teach the trainee how to physically manipulate the endoscopic instruments with their inherent fulcrum effect, secondly how to delicately to treat the tissues, thirdly to learn the anatomy of the region, and finally to learn the steps involved in a procedure. The first objective of manipulation can be met without the sophistication of a virtual reality simulator, and a simple box trainer may suffice (Chung et al., 2005; Windsor, 2007). The second objective, namely of learning how to treat soft tissues, is harder to achieve due to the computational complexity of dealing with deformable objects. Also it is a tremendous challenge to incorporate the widely variable changes in tissue properties, bleeding, the complexity of modelling sutures and the relationship of the sutures with the tissues(Basdogan, Ho, & Srinivasan, 1999; Picinbono, Lombardo, Delingette, & Ayache, 2000). Learning the anatomy of a region is much easier to achieve, though demonstration of the physical characteristics of organs and tissues rather than their simple relationships is somewhat harder. Finally learning the steps of a procedure is relatively simple in a simulator, as it is possible to prompt the user to complete each step, ensure they have completed it successfully and then lead them on to the next step.

Awareness of the particular attributes of a simulator will ensure that appropriate marketing of its capabilities can be carried out. In this manner the surgical community appreciates what the technology can deliver, and can begin the dialogue to improve subsequent iterations in the direction that the community sees as important.

3.4.2 Safety culture

The number of iatrogenic deaths or permanent disability has been described as around 2% of all hospital admissions(Merry & Seddon, 2006). Converting this data into an aviation industry model, shows there would be the equivalent of a Boeing 737 crash each month in New Zealand. FAA regulations do not specify how frequently pilots need to work within a simulator, however individual airlines have regulations which govern this usage. For Air NZ this amounts to 4 half days per 6 months. At this frequency of use, there is no detectable drop-off in performance for the pilots. Similarly at 9 month intervals there is no detectable decline in performance. However if intervals between simulation trainings are longer than 9 months performance is compromised, despite the fact these pilots are flying full time.. During around one third of all flights there is a significant threat posed by weather, air traffic, or circumstance such as a mechanical fault. The methods pilots use to manage these threats are a critical component in their job. Surgeons must also cope with unforeseen threats to the success of the procedure such as; finding more severe osteoporosis than initially thought, a more complex fracture pattern, or a weak femoral shaft that fractures while placing the femoral stem of a total hip replacement. Studies of performance in Advanced Trauma Life Support show that there is a significant deterioration in knowledge over time, but not in clinical skills(J. Ali et al., 2001).

Within the surgical community, audit plays a major role in providing quality assurance. In the past most audit simply meant carrying out morbidity and mortality meetings. By only examining cases where a complication arose, there is not the opportunity to analyse how effectively potential threats were recognised early and appropriate measures taken. More recently audits are expected to not only include morbidity and mortality events, but also systematic reviews of certain aspects of practice. This process is still usually individually undertaken, though audits are reviewed by a colleague. Audit is usually only required of surgeons having completed their training, with the surgical cases performed by trainees being included within the consultant surgeon's audit. From a patient care model this ensures that complications are identified and included in reporting. However from the trainees' point of view there is no requirement to conduct systematic reviews of their own operative performance. While certainly a step in the right direction, the possibility of missing valuable learning opportunities remains. A more independent and systematic method creates a better safety culture. Simulation has a role to play in this, but needs to be accepted by the community, and the process of integration into training paradigms will be smoother if the drive for simulation comes from within the community rather than being forced on the community by an external agency.

Leaders within communities are usually those people with significantly more experience. Within the orthopaedic community, surgeons who have been qualified for longer are more likely to have positions of responsibility within an organisation, partly because of the respect which they have earned, but also because they have had enough time to build up their practice, such that they have more time available to return to the organisation. Thus it was pleasantly surprising to find that those surgeons who had qualified earlier were less sceptical about the immanency of introduction of simulation into their practice than later qualifying surgeons and trainees. No further information concerning reasons why these surgeons held their views is available, however speculative reasons for this may include surgeons qualifying earlier having a broader perspective due to the longer timeframe of their practice. Having seen the introduction of technologies such as the image intensifier into the operating room, the tremendous advances in radiology, and the increasing role that computers have in many facets of life, perhaps they can see simulation as finally starting to emerge. Another reason may be the level of perceived sophistication of simulators required in order for simulators to be capable of filling a training need. There is further evidence for this when the results from the question looking at costs is examined. Another reason may be that they are more acutely aware of the pressures on achieving and maintaining a high standard of operative skill, in conjunction with the increasing focus on measurements, documentation and statistics which our society is leaning towards (Postman, 1993).

3.4.3 Changes in use of internet

The Advanced Research Projects Agency of the United States government developed a project to connect mainframe computers in universities. This network (called ARPAnet) was set-up in 1969, and subsequently developed into the internet. Since then the internet has dramatically changed many facets of our lives. We now use the internet to order our groceries, buy our cars, read the news, book air flights, as well as read journals, research new techniques, revise approaches and even identify whether a conference is worth attending. Thus surgeons and trainees are increasingly using computers to help them in tasks, and also change the way they approach and perform tasks. It is not surprising that 90% of respondents this survey accessed the internet weekly and 56% accessed the internet daily. Since this survey was conducted in 2003 these numbers will have increased substantially. The advantage of the internet is accessibility, a book sitting on a shelf at home cannot be read in the operating theatre tearoom, whereas more and more commonly the internet can be found at every desk.

3.4.4 Limitations of work hours

The nature of surgical training in Australasia is changing. It is now recognized that fatigue plays a significant role in deterioration of both cognitive and technical skills.(Eastridge et al., 2003) This level of deterioration has been likened to the effect of two glasses of alcohol on motor performance.(Williamson & Feyer, 2000) As a result, the long work weeks that were previously thought necessary for registrar training are no longer acceptable. In 1999, the Federal Council of the Australian Medical Association adopted a National Code of Practice regulating the hours of work, shiftwork and rostering for hospital doctors(Australian Medical Association, 1999). The New Zealand District Health Board Multi-Employer Collective Agreement has also stipulated limitations in the number of hours worked per week by surgical trainees in New Zealand.(New Zealand Residents Doctors Association, 2002)

American studies have shown that reduction in resident work hours leads to a better quality of life and improved scores by surgical residents in examinations assessing basic surgical education.(Barden et al., 2002) However, it is not certain how limitations on working hours for surgical trainees impacts on the acquisition of technical skills.(Barden et al., 2002) Trainees believe that the reduction in hours may lead to adverse outcomes in patient care and ability to acquire operative skills.(Whang et al., 2003) In addition the decreasing hours worked by trainees potentially reduces the amount of time available for learning from complex problems that evolve over weeks (Silen, 2003).

To overcome the negative consequences of work-hour reduction other means of obtaining experience should be sought. Within the apprenticeship method of training there exists an opportunistic style to training wherein some trainees may get an excellent and well-rounded exposure to multiple different cases, yet others may have a skewed experience if too much of their training occurs within tertiary level hospital environments. In comparison a well-designed curriculum method of training has the advantages of ensuring that all trainees are exposed to the core elements. The dilemma is that in removing trainees from their work environment to attend structured learning means they may miss out on other potentially valuable learning experiences. In addition the costs for trainees to travel from all over the country to attend such workshops, and requiring their hospital shifts to be covered by other registrars means that these intensive training sessions are limited to perhaps two training weekends per year. Virtual reality has the advantage of allowing trainees to remain at the hospital, and run through the training exercise when their schedule permits.

Within the survey the question was asked whether a simulator needs to be available 24 hours a day, with the median score being 5/10 and a large number of respondents strongly disagreeing with this statement (TABLE 3.2). This result may be due to a number of reasons. The respondents may have been answering the question for their own needs, and they are already in a position where they are unlikely to be working late hours. They may be thinking that a simulator would only be housed within a surgical skills centre, and as such although access to the centre may be available the hassle of getting the simulator to run would be too great. Finally they may be fixed in the paradigm that the trainee is unlikely to be able to get the simulator to run without IT input.

Web-based VR simulators potentially allow trainees to acquire a breadth of operating technique during down-times within their work schedule, thereby increasing the efficiency with which trainees can acquire skills through a curriculum based approach.

3.4.5 Role of simulators in training

Simulators have a role to play in surgical training, the size and extent of this role remains to be defined (Kneebone, 2003). Simulators have been shown to enhance performance over time and to be a subjectively useful experience for trainees, particularly novice surgeons.(Bloom, Rawn, Salzberg, & Krummel, 2003) As well, simulators provide an objective assessment of a trainee's performance, which contrasts with poor self-assessment of ability by many trainees.(MacDonald, Williams, & Rogers, 2003) Virtual Reality (VR) surgical simulators have been available for the past 13 years.(Ziegler, Fischer, Muller, & Gobel, 1995) However, simulators continue to have only sporadic input into surgical training, particularly orthopaedic trainees. This is in contrast to the propensity of the surgical community to pick up new methods and technologies in other areas of surgery, often before validation of the technique in controlled trials.(Gross, 1993)

One theory is that the proponents of simulation try to push too hard, ascribing that simulation will be able to take over the role of the apprentice type training. This can be seen as trying to usurp the role of the mentor. Although on a purely technical level a simulator can allow training towards a task, the role of the mentor cannot be replaced by a comtutor (sic).

Expertise in any psychomotor task only arises from practice. Kneebone et al (Kneebone, 2003) advocate deliberate and sustained practice, driven by motivation, with ongoing deliberate maintenance of skills.

3.4.6 Expertise through practice

VR Simulation allows an easy means of repeating a task, as there are usually no consumables, and the only ongoing expense is time. However this repetition of the task needs to be complemented by expert feedback. Within the tennis circuit the coach provides this feedback; within the operating theatre the consultant or senior registrar performs this task. This feedback may come from a simulator, however especially during training the rewards of having a mentor teaching not only technical skills, but also professional attitudes and behaviours are invaluable. The relationship between mentor and trainee is paramount, thus if there is a tremendous imbalance of power, the trainee is likely to perform poorly, ask few questions and learn little. Similarly if the mentor is pressured for time, they are more likely to become frustrated and take control of the operation rather than remain in a mentor role and supporting the trainee as they progress along the learning curve.

3.4.7 Motivation to practice

Motivation to practice, and reflect on the performance is another key component of gaining expertise. Generally this motivation must come from within, although at times the instruction of a superior is required. Forms of motivation to practice include discipline, competitiveness, fear of failure, and pleasure. Simulators can be used to provide each of these forms of motivation, however the extent to which a particular form of motivation drives an individual is highly variable. The success of the simulator at providing each of these depends on a number of factors.

The amount of discipline a trainee has is independent of the simulator, however the simulator will only be used if it fulfils the trainee's requirements for improving their skills. If the simulator does not fulfil this requirement they will seek other forms of practice.

Friendly competition can be encouraged if a simulator has an overall total score, allowing easy comparison between performances from different trainees. During part of the beta-testing of the Bon*e*doc simulator, trainees were given free access to the simulator. As a result certain trainees performed the various simulations a great multitude of times, in order to have their name at the top of the "high-scores" table.

Fear of failure will only drive trainees to practice on a simulator, if their result on the simulator is likely to be seen or analysed by the training committee or their supervising surgeon. If there is a fear of failure and there is a chance to refrain from performing these individuals will not use the simulator. Within the survey 15% of respondents felt that feedback from a simulator is threatening. This group of individuals needs careful attention. In addition there may be a bravado element in which some individuals privately have concerns but are not willing to speak out about them, for fear of appearing unsure of themselves. For these individuals introduction of a simulator may indeed be a stressful component. However the majority of respondents agreed with the statement that "feedback from a simulator is non-threatening" with a median score of 8.1/10, however the later qualified group felt this less keenly with a median score of 7.8/10 compared to 8.2/10, though this was not statistically significant. Conversely a trainee who fears failing in the real world, may leap at the chance to practice in an environment which is safe for the patient, and perhaps safe for them to practice in as well.

If a simulator is fun to use, is varied and in some way becomes addictive, and then trainees will practice on the simulator and ideally improve their real world performance. As computer gaming becomes more common within trainees, attention to this element may become more important.

3.4.8 Education

The ability for a simulator to provide information or training in a unique way will help to drive its acceptance and in turn its development. Examples of this include being able to practice angulation without exposure to radiation as well as easy metrics of angle and position calculation, as discussed below. Assessment is an important part of education, as it provides a goal for trainees to aim towards, as well as providing feedback to both the trainee and training committee about their progress. Simulators which are able to provide valid assessment of technical skills would provide a role which is currently relatively inaccessible in the current training program. The term Objective Structured Assessment of Technical Skills (OSATS) was coined by Martin et al in 1997 to describe the testing of discrete segments of surgical tasks using "bench models (Martin et al., 1997). This was one of the first attempts to objectively assess these skills as opposed to knowledge, this will be discussed further in Section 5.4.1.

3.4.9 Barriers to Uptake

Having discussed the drivers for uptake of simulation, the barriers must now be examined; possibly the greatest barrier to uptake of simulation is perception and presumptions. If the most sophisticated solution is created and an individual or community perceives a threat to currently used, accepted and valuable aspects of training, then there will be resistance to adoption of this new solution. Within surgery the traditional method of training has stood surgeons in good stead for decades. Despite this it is important that training is intermittently re-evaluated. This does not necessarily mean making changes, but the process of examining training structures critically will most often improve clarity of teaching, which in turn leads to clarity for the trainees. However this task of reassessing curriculum or training methods may be relatively arduous, especially given the fact that most members of training committees already have extensive work commitments.

A critical analysis of each new method of technology must be carried out, to ensure that the technology achieves the task it set out to achieve, is the most appropriate or cost effective method of achieving this goal, is sustainable, and available to trainees.

3.4.9.1 Appropriateness of Technology

Most current VR surgical simulators have been developed to teach endoscopic skills. There is some evidence that using a box-like trainer provides an equal learning environment at a fraction of the cost (Chung et al., 2005). It is important to identify the specific learning goal, and match the sophistication of the simulator to the goal. In this manner if the required goal is to teach trainees about the fulcrum effect of arthroscopy, the most cost effective method is a simple box trainer with a webcam (Windsor, 2007). Similarly endoscopic suturing can be taught equally or perhaps better on a simple box trainer than a $50,000 VR system, which captures huge amounts of data which may not be relevant to that particular trainees learning. Another example of using a simple method for teaching skills is giving trainees a box of dental floss, and asking them to practice hand-tying knots in their spare time, rather than waiting until the patient is anaesthetised, and the full surgical team is watching.

If box trainers have been shown to be equally as effective as VR simulators, as has been shown in a number of studies (Munz, Kumar, Moorthy, Bann, & Darzi, 2004; Sutherland et al., December 2003; Torkington, Smith, Rees, & Darzi, 2001) and more effective in others (Hamilton et al., 2002; Youngblood et al., 2005) then appropriate deliberation must be taken before a high tech solution is adopted. A paper by Berg et al 2007 describes many methods of using low cost, relatively low-fidelity approach to teaching skills (Berg et al., 2007). A key factor in setting up a simulation exercise is ongoing costs as have been mentioned in the background chapter. The advantage of using low-cost low fidelity physical simulators is that this may key-in to the very practical nature of many surgeons, who appreciate the innovation in using standard materials in a non-standard setting. An important addition in these settings is the value of the mentors; when they are well respected and enthusiastic they can help more reluctant trainees see the value in the exercise.

Another key factor within a simulator is it must be shown to deliver a feature which other technologies cannot provide. In endoscopic general surgery it is very hard to put a value on how well a trainee has performed as many of the outcomes are subjective rather than objective. An example of an objective score in laparoscopic simulators is measuring the distance along which trainees move the instruments. Measurement of this would be impossible in a box trainer. Most experts move the instruments more efficiently than novices (Woodrum et al., 2006), and consequently have shorter path lengths, in addition there may be less mental work-load once specific skills have been mastered (Carswell, Clarke, & Seales, 2005). Thus this measurement may be capable of discriminating between users with different expertise. However the feature it provides must be perceived to be important to the surgeon. If the feature is not immediately apparently important to the surgeon, then education regarding why the feature is important is required (Hamstra & Dubrowski, 2005). This requirement for education about a particular feature may prove to be the downfall for a product, as the educational component must either have great credibility or at least be aligned with the surgeons thinking.

Having installed a product, the continued use of the product is dependent on the simulator's ability to either provide ongoing teaching, i.e. it must have sufficient depth, or it must invoke some means of becoming 'addictive' .This facility is used within the video gaming industry. A means of provoking this addictive behaviour is the ability to provide a reasonably different experience with each virtual procedure. Thus similarly to the operative experience, once a surgeon feels they have mastered a particular procedure or fracture pattern, there is a tendency to become bored and no longer critically appraise their performance (Sochart, 1998).

3.4.9.2 Computer Literacy

A potential barrier to use of virtual reality simulators is a lack of computer literacy. However many surgeons are becoming increasingly familiar with computers, either to access radiology or other medical / non-medical information. A survey of 24 orthopaedic surgeons showed that they spent on average 1.4 hours per week accessing the Internet.(Sinkov, Andres, Wheeless, & Frassica, 2004) This survey indicated that 90% of the respondents accessed the Internet at least weekly and 56%

used it every day. Simulators that can run on desk-top computers may be easily usable by current surgeons.

Use of internet technology does not necessarily translate into overall computer literacy. Many surgeons will be comfortable with the internet for the tasks they are familiar at using, but would still remain far behind in terms of ability to troubleshoot software problems. Thus any simulator if it is to be used outside of a specific training centre with IT help on hand, it needs to be robust, and easy to use. This is reflected in the survey where the majority used textbooks and hardcopy journals to revise difficult or unfamiliar surgical approaches. Part of learning requires a familiarity with the source. Pages on the internet which are always changing and without a set structure lead to information overload, whereas having reread a book a number of times, the information is gleaned on subsequent readings with a lot less energy requirement. There is no doubt that as technology advances surgeons will become increasingly computer literate, however by their very cutting edge nature simulators will probably always be pushing the boundaries of many surgeons knowledge.

3.4.9.3 Changing Paradigms of Training

Despite their increasing computer literacy, orthopaedic surgeons still prefer to use textbooks and journal articles to revise difficult or unfamiliar surgical approaches compared to other methods by a ratio of 1.4 to one. This may reflect the educational methods used during their own training. There is little evidence as to whether these methods of revision are better or worse than other methods of maintaining and upgrading surgical skills. The use of artificial tissue, animal tissue, or cadaveric tissue has the disadvantages of high cost and, more importantly, limited access. In this only 42% of respondents indicated that simulators should be available at all hours. However accessibility was still regarded as important. Sixty percent of respondents indicated that simulator training should be undertaken frequently, rather than the intensive training that is more common on course based learning. This attitude bodes well for web based simulators, and is indeed a paradigm shift. The cost of delivering the current courses frequently rather than intensively would be exorbitant given the topography of New Zealand, however a shift for some of this training to the virtual world would be significantly less expensive, unless simple box trainers allow local hospitals to have training centres (Berg et al., 2007; Pokorny & McLaren, 2004). Even an expensive and hardware dependant simulator could be couriered between hospitals in the same way that specialised surgical equipment is currently shared around Australasia. For this to work the technology needs to be sufficiently user-friendly such that an individual surgeon or trainees could set up and use the simulator without additional personnel, complete the simulator task, and then send it on to the next hospital. Once again this would either have to be a very user friendly simulator, given most users lack of computer knowledge, and the lack of robustness in most current simulators.

3.4.10 Tasks

Part of the survey enquired about how important various tasks were simulated, this was an attempt to identify which areas should be focused on when developing a simulator.

3.4.10.1 Revising Anatomy

Only 80% of surgeons felt revising anatomy was an important task for a simulator. This probably reflects the fact that the majority of respondents used either anatomy or orthopaedic textbooks to revise approaches. However 36% of respondents rated this higher than 8/10, implying that simulators need to demonstrate the clinically relevant anatomy.

3.4.10.2 Providing Feedback on Performance

Within the clinical setting, there is limited opportunity to reflect on performance, due to the enormous number of variables which can affect surgical outcome. Within colorectal surgery Bowles and Watters (Bowles & Watters, 2007) have developed a system for simplified reporting of outcomes. In a similar fashion the New Zealand Joint Registry provides an opportunity for surgeons to compare their outcomes with their peers. This has been operating since 1998 and currently there are more than 43000 hip replacements and more than 29000 knee replacements in the registry (www.cdhb.govt.nz/NJR/). Thus surgeons are able to compare their complication rates with the standard set by other New Zealand surgeons; this data may reflect patient outcomes after a period of some years, such as how many years before patients with hip replacements can last before the implant requires revision. In contrast simulators have the ability to provide feedback in a very specific manner as well as instantaneous manner. A technique termed CUSUM (Cumulative Summation) analysis has been used as a visual objective analytic tool. This technique can be used to identify how long it takes to climb the learning curve as discussed in a paper by Young et al (A. Young, Miller, & Azarow, 2005).

3.4.10.3 Preoperative Planning

There is a subtle but important difference between preoperative planning and simulation. Preoperative planning involves a number of steps; firstly obtaining a template of the implant and a patient specific model; this model may be in the form of MRI, CT scans, Ultrasound scans, x-rays or a patient specific model derived from these; secondly crafting a plan for placement of these implants in the best possible position with associated reduction, osteotomy or soft tissue release as required. Most pre-operative planning systems show the location and angle of the screw from a number of different angles at the same time (Citak et al., 2007). Crafting this plan will be most appropriate as well as most efficient if it relies on avoiding the laws of physics; i.e. during the positioning of a screw, sideways motion of this screw as well changing the depth is permissible, and no penalties are applied for trying out a number of positions, or angles.

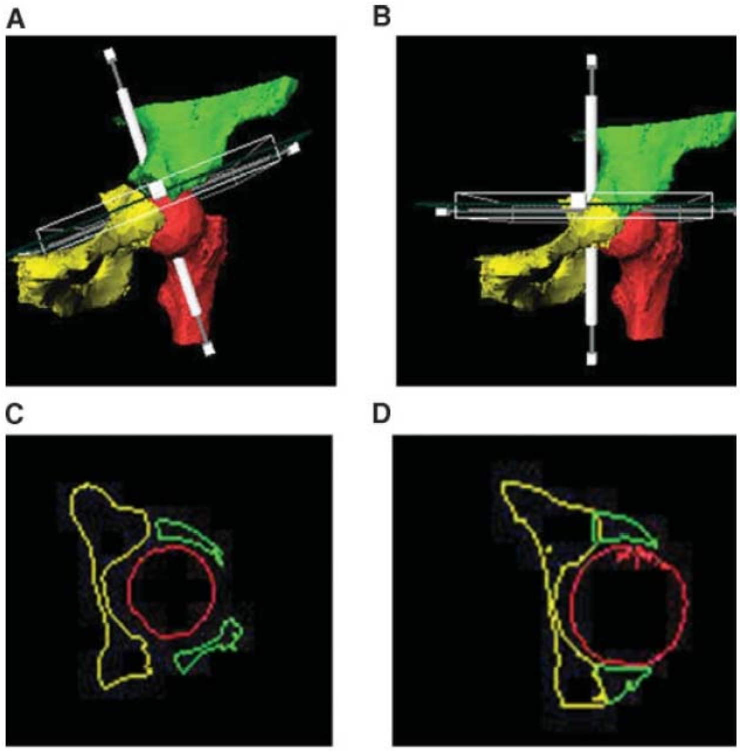

Figure 1. Fragments are segmented and color coded in both 3D (A) and 2D (B). After reduction, the fracture apposition can be visualized (C, D).

FIGURE 3.4: Surgical Planning Software Interface. From (Citak et al., 2007).

In comparison simulation involves the user being bound by the laws of physics, and paying the consequences for any manoeuvres which are not in the patients best interest. Examples of this involve requiring the user to completely withdraw a screw before changing the angle, and only being able to see the screw from a single viewpoint at a time. Within virtual reality it is possible to allow both pre-operative planning and simulation. Thus having created a patient specific model, the user could overlay the implant in the best possible position in "preoperative planning mode" and then switch to "simulation mode". The user could then practice placement of this implant governed by the steps which are performed in the real world. It would then be possible to compare simulated performance with the preoperative plan.

It should be pointed out that both pre-operative planning and simulation can be carried out with very little or no technology. An example of this might be the procedure of closed relocation of a shoulder dislocation. The trainee conceptualises what the anterior dislocation of the shoulder looks like radiographically, having simply examined the patient. Then before providing analgesia and/or sedation the trainee will run through the relocation manoeuvre in his/her head as well as alternative relocation manoeuvres should the chosen method fail. Then hopefully, the trainee will perform the actual procedure fluidly.

The results from this survey show that many surgeons felt the task of pre-operative planning was relatively important, however the fact that this did not achieve the best rating may reflect the fact that they are still satisfied with their current means of preoperative planning.

3.4.10.4 Practicing Angulation/Spatial orientation

Many procedures within orthopaedics rely on placing implants in the correct place and with the correct orientation, thus it is not surprising that this task was rated highest within the survey. Within training there are limited opportunities to practice this angulation outside of the operating room. This lack of opportunities is especially evident if you take into account image guided surgery. Studies such as those by Palm et al (Palm et al., 2007) show that unsupervised junior registrars operating on technically demanding proximal femoral fractures have more complications than those fractures operated on by senior or supervised junior registrars. These authors point out that this procedure is an important part of the training of a junior trainee. From the overall healthcare perspective it is vital that junior trainees are allowed opportunities such as this to improve their skills. However it seems appropriate from an individual patient's point of view, that any method of helping a trainee along the learning curve without risk to this patient is warranted (Morgenstern, 2005).

3.4.10.5 Image Intensifier guided

There was a significant difference between the earlier and later qualifying surgeons with the strength to which they agreed with the statement that image intensifier guided procedures should be simulated, with the earlier qualifying surgeons again being keener on this task being simulated. This may reflect their experience of observing the introduction of the image intensifier into the theatre, but is probably more likely their greater experience at watching junior trainees struggle with understanding where they are in 3 dimensions.

3.4.10.6 Uncommon procedures

Within continuing education, there is an appreciation that there is little need to attend workshops for procedures which you perform regularly, as unless it is a really advanced workshop it is unlikely that any real benefit will result. However those procedures which are performed less commonly are the ones most suitable for either attending a workshop, or practicing immediately prior to the surgery, in order to avoid natural deterioration in performing a task. Indeed although no-one forgets how to ride a bike, there are not many people who would like their first bicycle ride in 5 years to be during rush hour traffic without riding around a park first. Within this survey it is interesting to observe that simulators for uncommon tasks was not rated higher, this may reflect a belief that if the simulator required re-learning in itself, then it would be more efficient and equally effective to read an operative manual.

3.4.11 Training Intensity vs. Frequency

Simulators can be used in one of two ways; either intensively or frequently. Intensive training is most effective in rapidly up-skilling a trainee in a particular area, however if the interval between the training exercise and the real operation is too great, then the benefits of the training may be lost, similarly to that found with aviation flight simulation, as discussed previously. Training performed frequently (having reached a satisfactory level of performance by training intensively) is obviously the most beneficial (Ross, 2006) but the logistics of providing this type of training need to be examined more closely. Currently most simulators are situated within surgical skills centres and as such are not accessible to trainees on a frequent basis, as they require personnel to run them and usually a mentor to guide the trainee, as well as running costs such as consumables. In contrast a web-based simulator has the advantages of accessibility at any hour, removes the requirement for both support personnel and mentors, and does not use any consumable items.

Within the survey 15% of respondents scored the visual analogue scale between 0 and 1/10 signalling that training should be undertaken frequently (FIGURE 3.5). This has dramatic implications with regards to costs of providing this training, unless a web-driven model of simulation is utilised.

FIGURE 3.5: Box and whisker plot showing respondent's views with regard to the mode of simulator use.

3.4.12 Simulation's role in credentialing

Another means of achieving buy-in is to somehow link performance on the simulator with credentialing. This is achieved within the aviation industry. Although the FAA does not require pilots to use simulators, airline companies must show the FAA that they have a policy of encouraging a safety culture. Thus part of the company's policy is requiring pilots to maintain their 'virtual flying hours'. Obviously there is cost associated with having a pilot spend time in a simulator but the industry is so heavily supportive of the simulator training that this cost is borne. Interestingly, having developed simulators with 6 degrees of freedom, there is emerging evidence that at least part of the pilots simulation training can be performed on a simulator which is ground based, and vastly cheaper (Robinson & Mania, 2007). This is one of the first examples of realising 'lower fidelity' experiences can be equally beneficial.

Within the medical community the requirement for simulator certification is still a while away. This is in part because studies have not yet shown the importance of time on a surgical simulator, but also in part because the simulators themselves are relatively unsophisticated. Another issue is the reluctance to adequately take stock, or to examine surgical performance too critically. Indeed the risk of too much focus on performance means the natural ability to perform may be lost. In a similar manner a top sports-person may continue performing badly because of excess media and coach attention on their supposed 'lack of recent form'. In addition there are so many variables which cannot be accounted for, and a poor result for the patient may not be due to anything the surgeon has done. In comparison with the aviation industry where there are an incredible number of protocols, each surgical case is different, further clouding the ability to draw exact comparisons.

A simulator has the ability to be used in accreditation as it is possible to remove the variation between patients and essentially compare performance on the same patient. Chapter 6 will describe the experiment whereby all New Zealand trainees operate on the same slipped capital femoral epiphysis.

Within this survey it was clear that the orthopaedic community in New Zealand did not see simulation as being able to be used for accreditation, however it must be borne in mind that only 4 surgeons had seen a simulator, and none of these had been an orthopaedic simulator.

3.4.13 Realism

One common criticism of current VR surgical simulators is that they lack realism. Survey respondents felt that a realistic view of the operation was the most important feature of a simulator, a response that seems intuitively correct. However, the available research suggests that higher levels of realism in a simulator do not necessarily produce better learning. For example, practice with CathSim, a highly realistic intravenous cannulation simulator did not improve the ability of medical students to cannulate real patients.(Prystowsky et al., 1999) Conversely, MIST-VR (Virtual Presence, London, UK), a 'bare bones' laparoscopic simulator, which uses abstracted graphics, has been shown to improve performance in specific tasks performed during subsequent real laparoscopies.(Grantcharov et al., 2004; Seymour et al., 2002) Overall, the minimum requirement for task fidelity, or realism, has yet to be determined and may prove to be different for simulations of different tasks.(Cosman, Cregan, Martin, & Cartmill, 2002)

3.4.14 Stage of Training

Simulators have the potential to be used by surgeons and trainees for acquiring new techniques and maintaining skills at all stages of their career. More than 25% of respondents felt that simulators should be used in all of the categories above junior trainees. The group seen to have the most use for a simulator is the advanced trainees with 37% of respondents indicating this group should use a simulator. Of note more of the earlier qualifying surgeons thought that surgeons should use a simulator, while more of the later qualifying surgeons and advanced trainees thought that the advanced trainees should use a simulator. This may reflect a feeling that each of the groups could see the benefits of a simulator for their own use.

3.4.15 Cost

3.4.16

A significant factor in developing a simulator is the ability to recover costs, as discussed in Section 2.2.3. Although only 4 of the surgeons had tried a surgical simulator, and these were research only simulators, it is still valuable to investigate the expected price which surgeons feel should be paid for a simulator. As can be seen on the FIGURE 3.6, there is a reasonable spread of responses, the later qualifying surgeons have expectations of higher costs than the earlier qualifying surgeons. The median score placed the cost of a simulator in the $10,000 to $30,000 range. A simulator which costs this much, is unlikely to be purchased by most hospitals, especially provincial based hospitals. With this expense it is likely that only the larger surgical skills centres would be able to afford such a simulator, unless simulations was mandated in some way by the medical council or surgical college. It is reasonably unlikely at this stage that a simulator which requires an investment in hardware could be produced to sell for less than $10,000. Thus there exists a dilemma; should a simulator be produced which matches the expectations of surgeons, but which economically may not be viable, or should a simulator be developed which is economically viable, but costs considerably less than what surgeons expect to pay. In the latter case, if the cost is significantly less than the surgeons' expectation then they may undervalue the simulator and write it off as not being fit for the task.

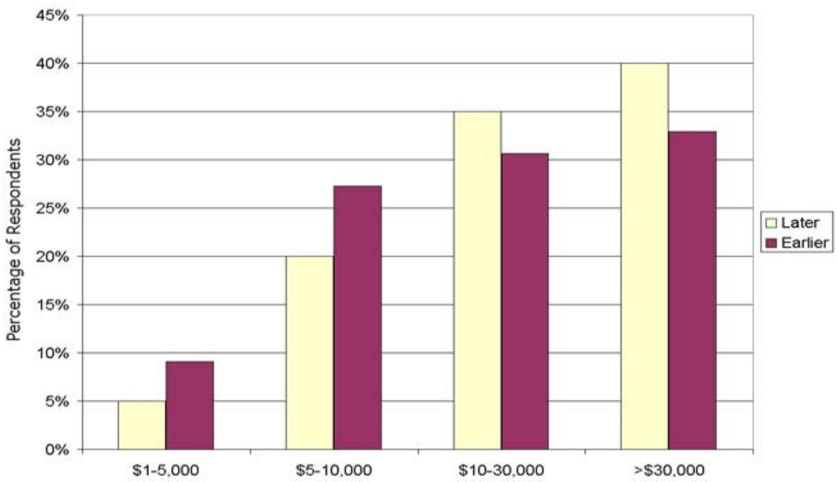

FIGURE 3.6: Histogram showing the price respondents expect to pay for a simulator.

3.5 Summary

In summary this chapter present the results of a survey of New Zealand orthopaedic surgeons and trainees which drew a 68% response rate. Most respondents indicated that simulation can provide an effective means to enhance feedback in a non-threatening way, although few had had any direct exposure to surgical simulators. The barriers to successful simulation were perceived to be significant, with most respondents disagreeing with the statement that simulators may be used for accreditation in the next 5 years. Contrary to the original hypothesis, earlier qualifying surgeons saw a greater role for surgical simulation in the near future, both in education and in accreditation. While this survey was being conducted, development of the Bon*e*doc simulator was taking place concurrently, in this manner the results of this survey were not available during the main development phase of the simulator.

The following chapter describes the development and features of Bon*e*doc thus enabling analysis of the extent to which features of Bon*e*doc align with the attitudes and conceptions of New Zealand orthopaedic surgeons and trainees.

4 DEVELOPMENT AND FACE VALIDITY

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

4.1 Introduction

This chapter describes the development of the Bon*e*doc simulator. The simulator allows users to practice image guided orthopaedic surgery on the hip. The first module simulates a procedure for fixing fractures of the hip. An overview of the clinical background to treatment of hip fracture is first described and then the remainder of the chapter covers two aspects: firstly it details which real world objects and problems have been incorporated, as well as the reasons for and technical details involved in producing a simulator which can run on the relatively low-spec computers found within the hospital environment. The second aspect covered is the face validity of the simulator, describing how closely users felt the simulated operation resembled the real operation of fixing a hip fracture with a sliding screw and plate.

4.2 Background

Hip fracture (or more accurately fracture of the femoral neck) is one of the most common fractures in the elderly patient in New Zealand (Stephenson, Langley, Campbell, & Gillespie, 2003). The number of hip fractures is projected to increase further as the percentage of people over 65 years old rises from 12% of population in 2004, to an estimated 25% of population in 2021 (Dunstan, 2005).

This fracture usually results from a simple fall. There are a multitude of factors which can contribute to falls, such as those within the environment (e.g. slippers), those related to co-morbidities (e.g. cardiac arrhythmias), and those related to iatrogenic causes (e.g. multiple medications). Whether a fall results in hip fracture is related to the bone density of the patient. Osteoporosis is not well recognised and consequently treatment for this condition is underutilised in New Zealand (Horne, 2007).

Hip fracture has a significant impact on the elderly. The 12 month mortality following hip fracture lies between 18.8-32% (Thwaites, Mann, Gilchrist, McKie, & Sainsbury, 2007; W. Young, Seigne, Bright, & Gardner, 2006). Less than 50% of patients regain their pre-fracture level of morbidity at 12 months.

Hip fracture is treated surgically in a number of ways, dependant largely on the fracture pattern and the patient's pre-fracture physical condition. Displaced fractures in the subcapital region of the neck require treatment which replaces the femoral head. This is because the blood supply to the femoral head is usually compromised, and the femoral head must be replaced to avoid the complication of avascular necrosis.

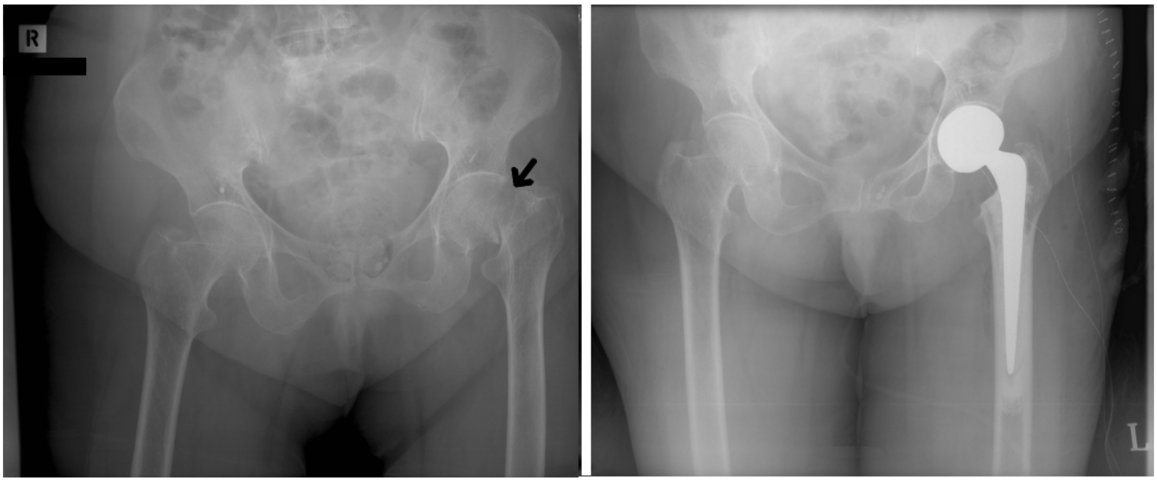

FIGURE 4.1: A displaced sub-capital fracture (arrow) treated with a hemiarthroplasty as the patient had reduced mobility.

The head of the femur only is replaced in the operation of hemiarthroplasty as seen in FIGURE 4.1. This operation is most suitable for patients who are less mobile, or have conditions such as dementia which may cause them to move their hip in an awkward angle and dislocate the prosthesis.

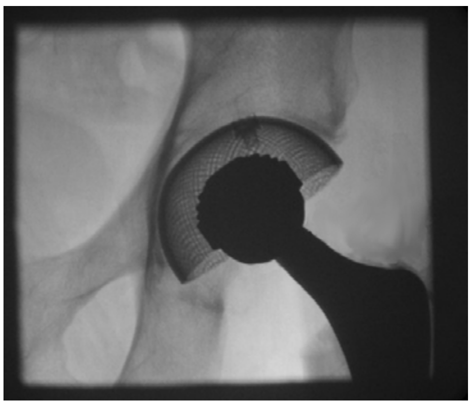

FIGURE 4.2: A hip arthroplasty showing replacement of the articular surfaces of both femoral head and acetabulum.

In the procedure of hip arthroplasty (or total hip replacement) both the femoral hip and the acetabulum are replaced, as seen in FIGURE 4.2. This operation is preferable in mobile patients as it avoids the risk of arthritis in the acetabulum. However this is a more substantial operation, and has a greater risk of dislocation due to the relatively smaller femoral head prosthesis.

Femoral neck fractures distal to the midcervical region (as well as undisplaced subcapital fractures) are treated with screw fixation. This screw fixation is either in the form of multiple cannulated screws, or a sliding screw and plate type of implant, such as the Dynamic Hip Screw. The advantages of this procedure is that it is relatively fast and involves less disruption to the fibrous joint capsule of the hip and muscles attaching about the hip. In addition the patients articular cartilage remains intact, and thus once the fracture has healed, the patients do not generally suffer from joint pain.

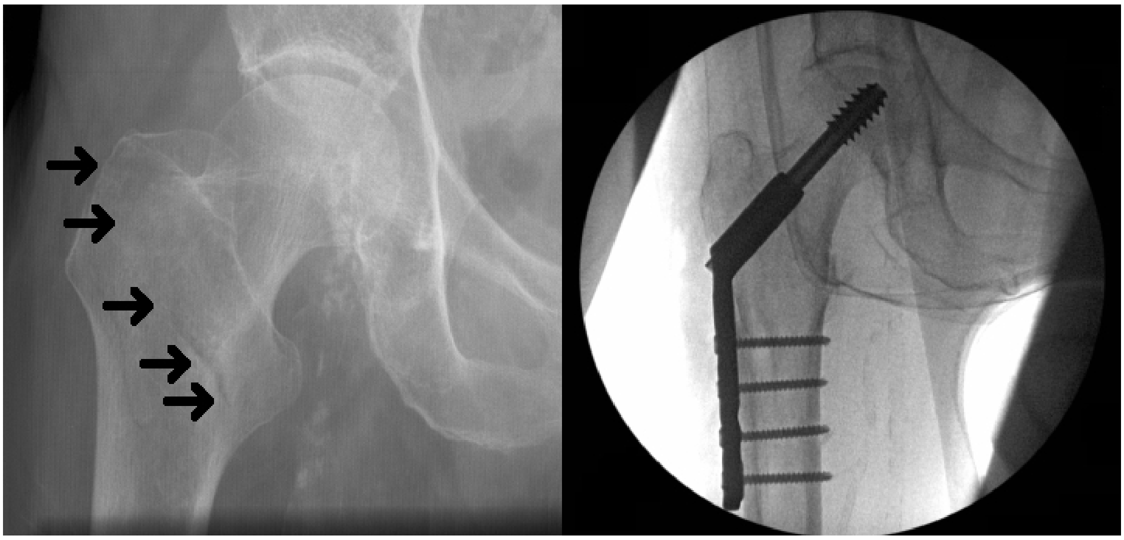

FIGURE 4.3: An intertrochanteric fracture (arrows) fixed with a Dynamic Hip Screw®.

Auckland City Hospital has a catchment area of around 30% of the Auckland region's population which equates to 370, 000 people. There are around 300 patients admitted to the hospital with a fracture of the femoral neck or trochanteric region per year (averaged over past 5 years). Of these 17 patients received a hip replacement, 113 patients received a hemiarthroplasty, around 170 patients received a sliding screw and plate. Thus almost every day, an operation for a fractured hip will take place, and at least every second day, this will involve the sliding screw and plate type of procedure.

4.3 Development

The development of the simulator has occurred in a number of stages, and these will be discussed in turn during this next section. It should be noted that this development was an iterative process, however this section will describe the process consecutively.

The first stage was to create suitable virtual models of patients on which the user could operate; this involved development of a single model of a patient's anatomy and then morphing this to other patients. The second stage was the development of the general components of the simulator, this involved making sure the software and hardware found within the hospital environment could cope. The third stage was to ensure that each necessary part of the real operating theatre was included within the surgery, this includes the traction table on which patients lie, the image intensifier which captures the x-ray images, and finally the orthopaedic implants which are used within the operation. The fourth stage involved recreating each step of the procedure of a sliding screw and plate fixation for hip fracture, from reducing the fracture anatomically, incising the skin, drilling a guide-wire, placing the definitive lag screw and plate and finally affixing the plate to the shaft of the femur with screws. The final stage of development involved providing objective results for each of the steps of the procedure.

4.3.1 Virtual Patients

The first stage of development involved the creation of the virtual anatomic models of the femur and pelvis. This involved creation of a generic model of the pelvis and femur, and then adaptation of the generic model to various 'virtual patient' femurs utilising the host mesh technique. These 'virtual patients' were based on data from the Visible Human Project® and data from scans of dry bones.

The generic models of the femur and pelvis were created by digitising numerous points from plastic Somso® anatomical models of these bones. From these data-points cubic Hermite Finite Element Models were created by Stephen Thrupp, a medical student member of the Bioengineering Institute. The use of a cubic Hermite description for modelling anatomy rather than the usual Lagrangian finite elements has several advantages. These advantages include a decrease in the number of elements required to capture the geometry of the femur from around 120,000 elements for a Lagrangian mesh compared with 384 for the cubic Hermite mesh, and importantly avoids problems with pixelisation as there is continuity of nodal values (C0 continuity and their first derivatives (C1 continuity), and creates smooth shading as the surface normals are interpolated (Fernandez, Mithraratne, Thrupp, Tawhai, & Hunter, 2004).

4.3.1.1 Host Mesh using the Visible Human Project® dataset

The generic femur model was then customised to the Visible Human Project® dataset using the host mesh technique. This technique uses 24 landmark points to customise the generic femur to patient specific data, using a normal desktop computer. The generic femur is embedded within a host mesh, in this case 3 cubes (FIGURE 4.4).

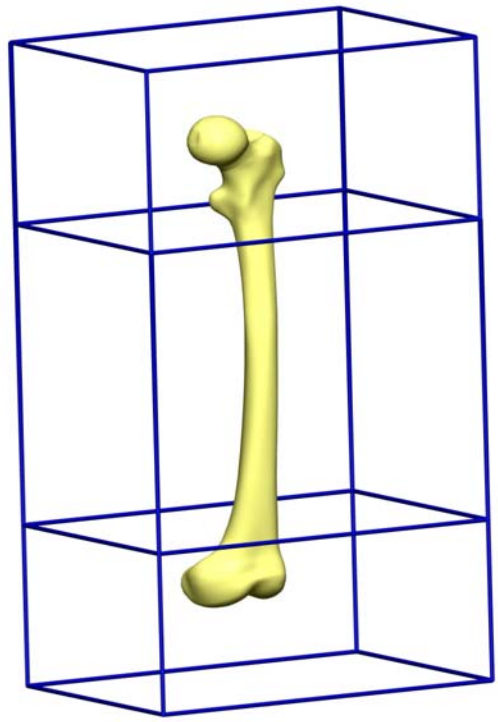

FIGURE 4.4: The generic femur embedded within the host mesh (blue frame).

Landmark data points on the generic femur were identified as detailed in Appendix C. Images of transverse cryomacrotomed sections from male specimen of the Visible Human Project® of the National Library of Medicine (Spitzer, Ackerman, Scherzinger, & Whitlock, 1996) were obtained. Images were selected from the project at 5 mm intervals from section 730mm to 1345mm (as measured caudally from the top of the head). These sections incorporated the pelvis and femur (FIGURE 4.5).

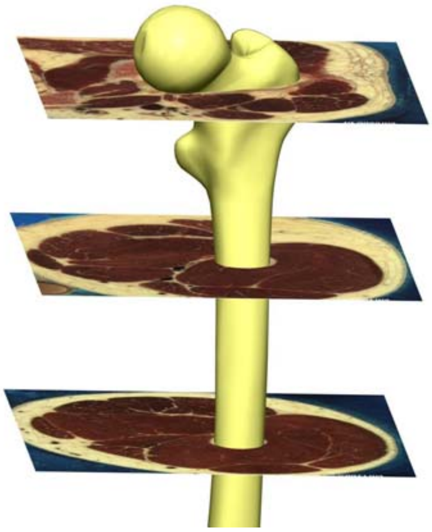

FIGURE 4.5: Images from the Visible Human Project® in the same 3-Dimensional space as the customised femur.

On these slices target points corresponding to the aforementioned landmark points were identified (FIGURE 4.6). A least squares algorithm was then used to minimise the difference between these landmark and target points. This algorithm consequently changed the shape of the host mesh (FIGURE 4.7), and as the femur was embedded within this host mesh, the shape of femur was subsequently 'morphed' to resemble the shape of the new femur. (FIGURE 4.8)

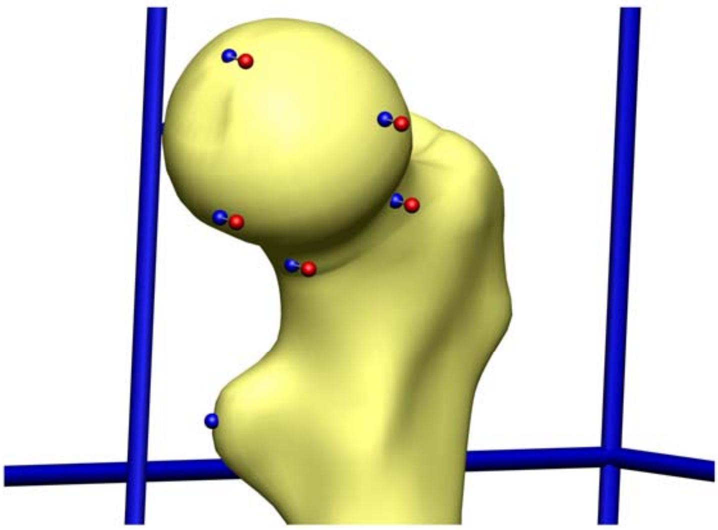

FIGURE 4.6: Landmark (Blue spheres) and Target (Red spheres) points are identified on generic femur and patient data. The image slices from the Visible Human Project® are not drawn to simplify the figure.

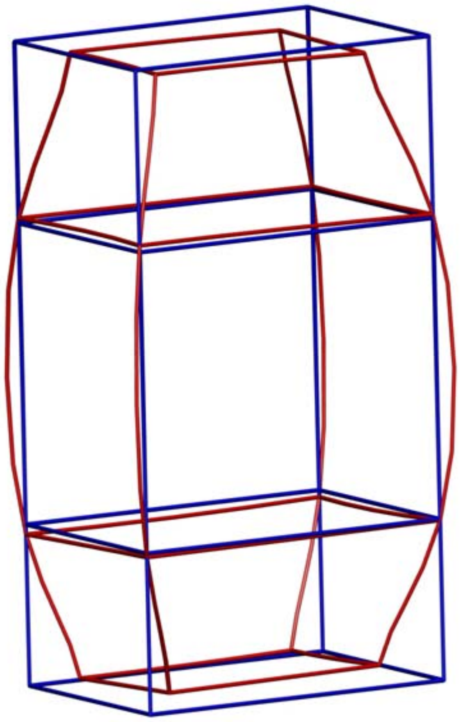

FIGURE 4.7: The host mesh (blue frame) is transformed to the customised mesh (red frame) by a least squares algorithm to minimise the distance between landmark and target points.

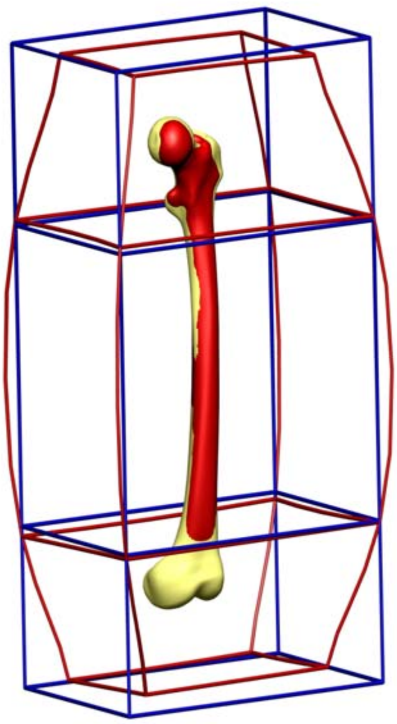

FIGURE 4.8: The generic femur (bone coloured) is transformed to the patient specific model (red bone).

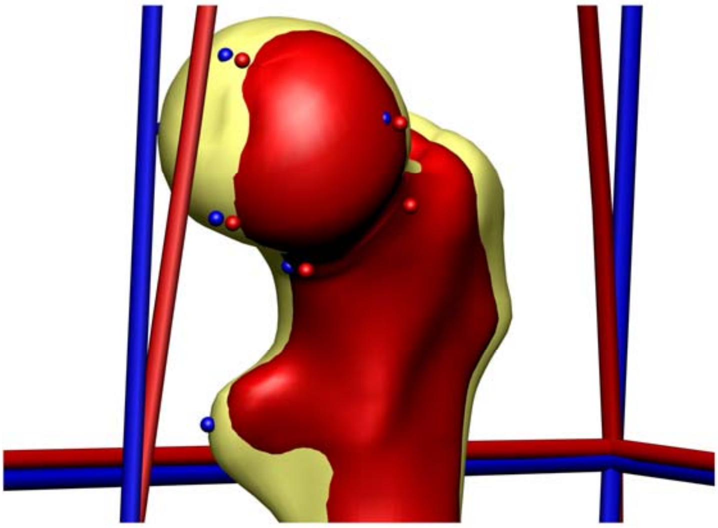

FIGURE 4.9: Close-up view of generic (bone coloured) and patient-specific (red coloured) femurs.

To validate the host mesh technique four dry bone femurs were scanned using the Polhemus Fastscan™ Laser Scanner (developed by Applied Research Associates NZ Ltd) (FIGURE 4.10). From this cloud of data, the relevant target points were identified and 'patient specific' femurs were created. The geometries of these were compared with a fit of the generic femur using the entire cloud of points. The root mean square (RMS) difference between these two fits was 3.09 with a standard deviation of 0.15mm.

FIGURE 4.10: The Polhemus FastScan™ Laser Scanner used to validate the host mesh method.

As CT or MRI scans produce multiple axial sections, the CMISS software (a finite element modelling package developed by the Bioengineering Institute, University of Auckland www.cmiss.org) is able to create patient specific geometry (Fernandez et al., 2004; Shim, Pitto, Streicher, Hunter, & Anderson, 2006), in this way femur geometry from patients could be incorporated into the simulator. The impact that fractures and their relative displacements have on the host mesh technique however remains to be addressed.

Having produced these five different femurs from the dry-bone and visible human data, fractures of the proximal femurs were then manually created by adjusting nodal positions (interpolating where required), and separating the femur into two parts. A subcapital, basicervical and intertrochanteric fracture of each of the five different femurs were thus created, and a total of 15 different femurs were then available (FIGURE 4.11). These fractured femurs were then exported as VRML objects for use within the simulator.

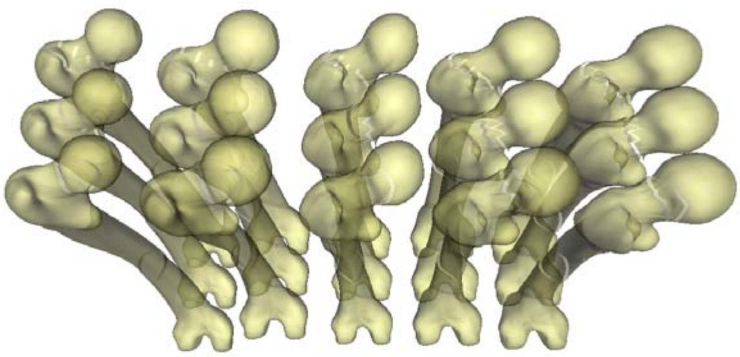

FIGURE 4.11: The set of 15 virtual femurs ready for importing into the simulator.

4.3.2 VRML interface

The main simulator interface was written in Virtual Reality Mark-up Language (VRML), utilizing JavaScript for decision logic and state management. VRML was selected on the basis that it is backwards compatible to computers running windows 98, as well as Linux and Mac OSX. Most if not all computers within the hospital environment are able to interpret VRML with the appropriate plug-in.

4.3.2.1 Plug-in

The simulator runs in Internet Explorer (Microsoft Corp, USA) using the Octagaplayer (Octaga AS, Norway) plug-in. The simulator can be accessed over the Internet or run from an installation on a stand alone computer. The total size of the download is around 4 MB. The main file for the simulator comprises around 8,500 lines of code, with around 850 routes between variables, and amounts to a total of just of 300KB. By comparison, this thesis is also around 300KB if only the words are saved as a text file. The code could probably be made more efficient, but the power of CPUs and graphics cards cope with ease, and hence strenuous effort in this regard has not been applied.

VRML files describing the geometry of the various parts of anatomy are located in a separate directory, and account for the majority of the download size. By storing these geometries outside the main file, these external files can be changed to provide different or updated virtual patients, and indeed different VR operating theatres as required. These external files may reside on a multitude of servers. Thus if a server is offline the file may be accessed from a subsequent server. This allows a certain amount of "fault-tolerance" as well as the ability to individualize and update each procedure.

4.3.2.2 Javascript

Virtual Reality Markup Language allows the incorporation of JavaScript within the code. This JavaScript permits logic control, such that for example pressing the x-ray button on the console, changes the appearance of the bones, stops the browser from rendering the skin and operating theatre, alters the appearance of the implants, calculates the viewpoint associated with the x-ray machine and finally renders the image, as well as recording the number of x-ray images acquired. Within the simulator there are in the order of 85 different scripts, with numerous different functions within each of these scripts. Each of these scripts will have outputs which in turn are routed to other scripts, thus allowing divergence of logic as well as convergence. Some of the scripts generate new VRML code on the fly allowing for tailor-made implants specific to each procedure. Other scripts generate and save HTML code, or post the results of the simulation to a web-server.

4.3.2.3 External storage of results

A key feature of the simulator is that the results from each operation are recorded. In order to be as robust as possible, this information is stored in two places; firstly the results are posted to a web-based server within the hospital, and a secondly a copy is saved to a local drive on the computer. The exact details of these results are discussed in a subsequent section.

4.3.2.4 Navigation around suite

The simulator incorporates all relevant tasks to pinning of a hip fracture, from fracture reduction through to placement of the cortical screws. In order to accomplish these tasks the trainee is able to move around within the operating theatre and view the various parts of the operating room from a number of different viewpoints. These include views from the adjustment controls of the traction table, the radiographer's viewpoint, the x-ray image and the surgeon's view (Figures 4.9 to 4.12).

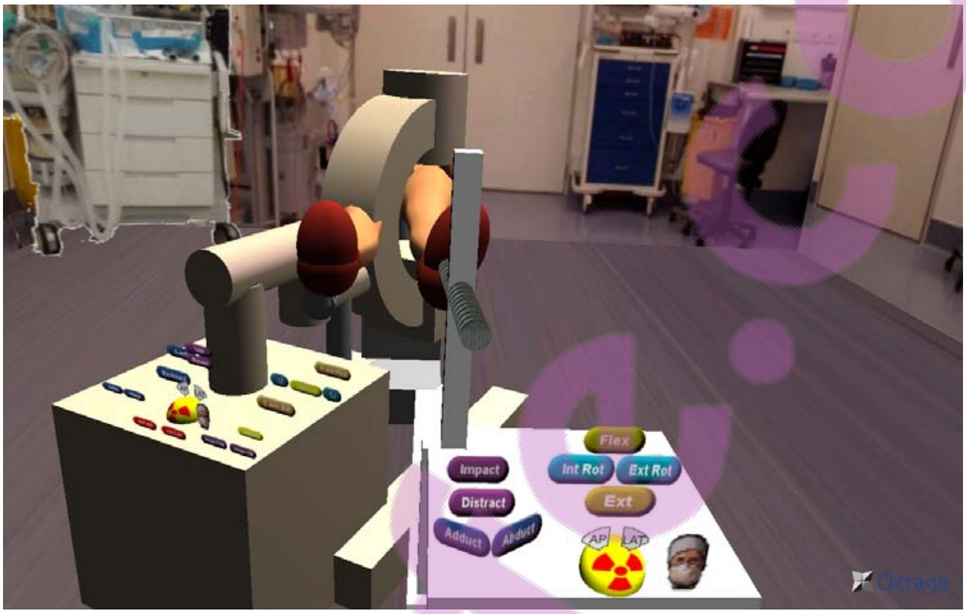

FIGURE 4.12: The view from the traction console.

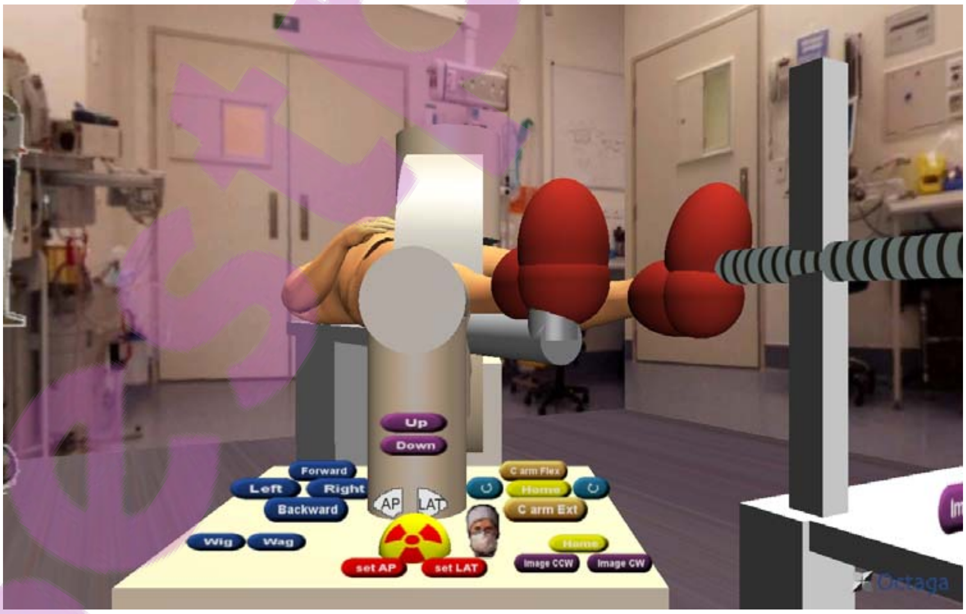

FIGURE 4.13: The scene from the radiographer's viewpoint.

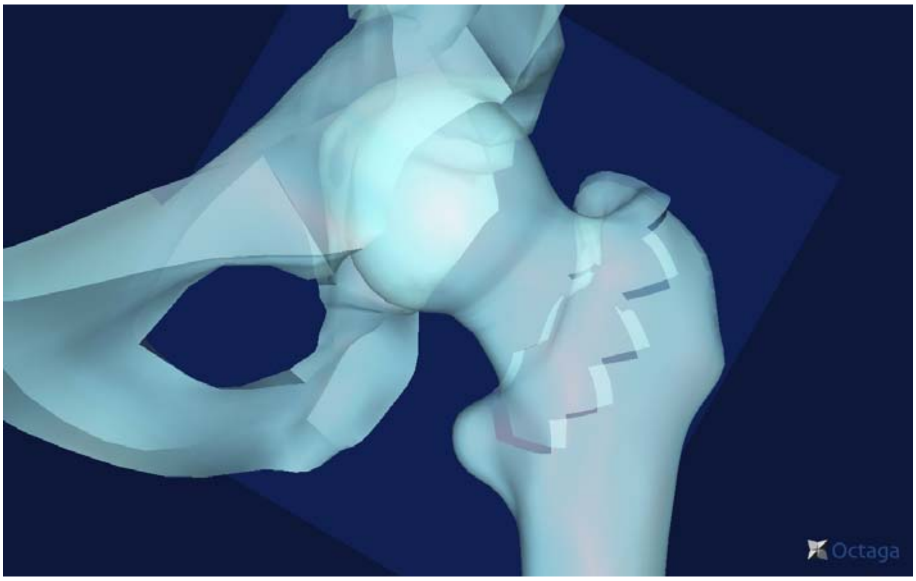

FIGURE 4.14: Virtual x-ray showing an intertrochanteric fracture.

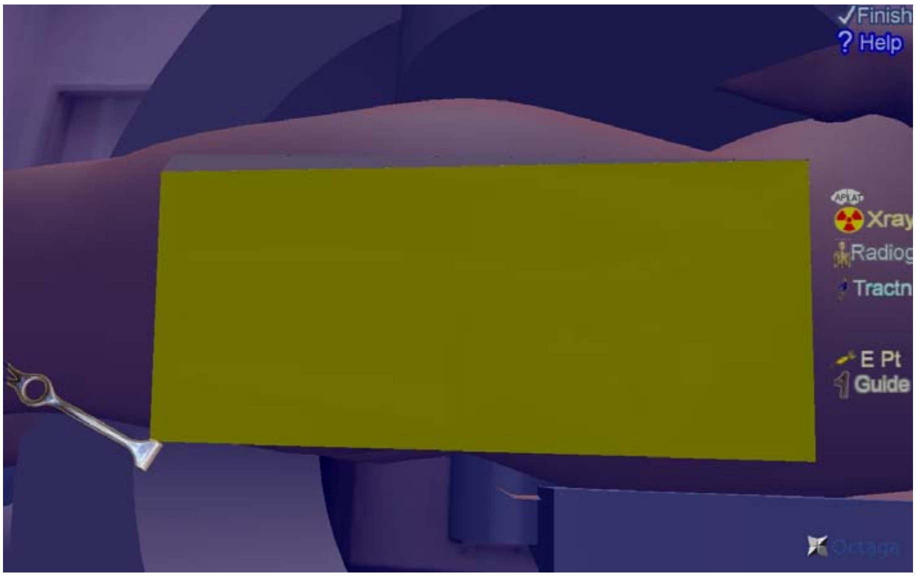

FIGURE 4.15: The surgical view.

A vital component is thus the ease of navigation (or moving) around the virtual operating suite. The simulator is adaptable to two types of users, the novice user and the user with more computer gaming experience. The novice user can easily find themselves lost if it is possible to move around too much within the simulator. For this purpose the simulator defaults to a mode whereby no navigation of the surgeon is allowed and instead certain predefined Viewpoints are allowed. Users who have more 3-Dimensional gaming experience will find this constraint frustrating, as the ability to view the operative scene from a slightly different angle provides more information and realism.

To satisfy these two types of users there is a toggle-button which allows the experienced user to remove this navigation constraint.

For both novice and experienced user flipping between these viewpoints is achieved by clicking buttons which are either on the traction console, the image intensifier console, or on the 'Heads Up Display'.

4.3.2.5 Requirement for simulator to run in hospital systems

The simulator was designed to work under the constraints of the computers found within the hospital system. As such there was a need to adjust the amount of realism within the simulator such that it does not overwhelm the specifications of these computers. Having said that, all the required elements within the operating room are modelled, and the simulator uses a similar interface to computer gaming, rather than the menu driven format of desktop software. All required objects such as skin, bones, traction table and image intensifier found within the operation could be modelled as non-deformable objects, and consequently the demand on computation resources was reduced dramatically, allowing the software to run with acceptable frame-rates of at least 15 frames per second even on low-specification computers.

4.3.3 Simulator Construction

This section describes various objects found within the real operating room when a hip fracture is fixed using a sliding screw and plate implant. Following each of these real-world descriptions, the techniques used to simulate these aspects in the virtual world will be addressed.

4.3.3.1 Construction of Virtual Operating Suite

Two criteria were used to decide whether an object from the real operating theatre needed to be included within the simulator. These criteria were; those components required to execute a step for the procedure were included, and those components which enable the trainee to feel more immersed.

The backdrop for the virtual operating room comprises five images (the four walls and floor) which are textured onto 2-dimensional flat elements (FIGURE 4.16). The effect is that the trainee can pan around the full 360 degrees and always see a valid viewpoint. The images were taken in a real operating suite using a standard digital camera, ensuring that items which are modelled were hidden from view in all images. These images required little manipulation, as each image was taken while ensuring the horizon (in this case a line around the walls of the theatre) was at the same level on each image. Once textured onto the wall elements, the user may move around the suite, with the calculations for perspective being performed by the graphics engine of the computer. The advantages of this method are that it requires very little computation to render this backdrop, and the objects on the wall, such as the computers, whiteboards and light switches appear very real. This realism would lessen if the user got close enough to the walls such that they were able to identify the fact that for example the shelf on the wall was just a texture rather than an individual object.

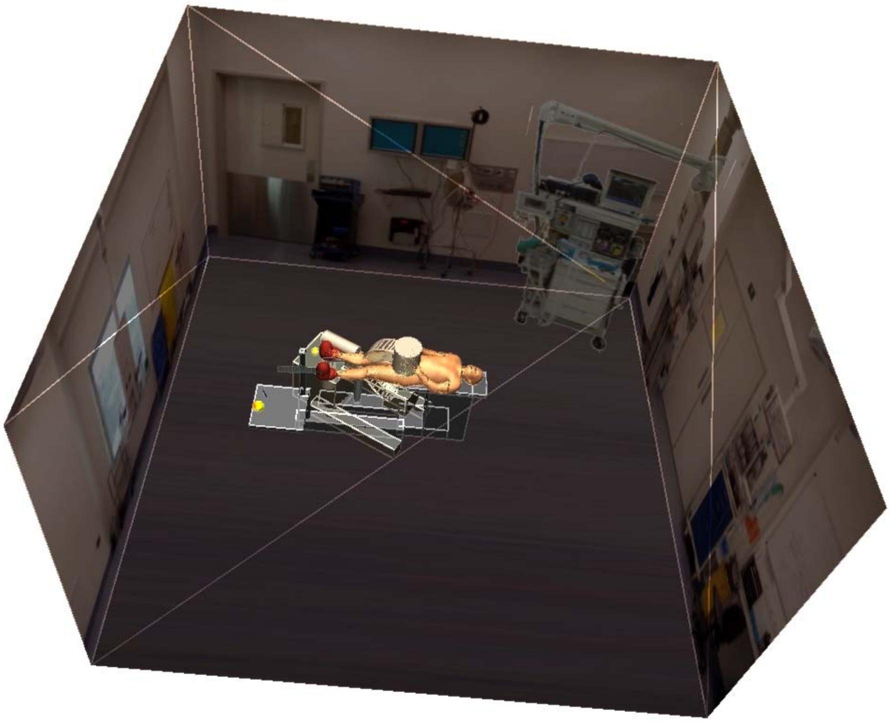

FIGURE 4.16: The virtual operating room is modelled with 4 images for the walls to increase realism.

In other cases use of obscuring adds to the illusion of 3 dimensions, by rendering an object in the foreground of the operating theatre, and then moving the viewpoint it will obscure different parts of the background and increase the illusion of depth perception and consequently the feeling of immersion. This is a standard film making technique. Within the simulator the anaesthetic machine has been modelled using a VRML 'Billboard' node. This is a type of node which rotates such that it always faces the user. In the case of the anaesthetic machine a photo of the real anaesthetic machine was taken, and converted to a Graphics Interchange Format (.gif) image which was textured onto a 2 dimensional plane surface. The Graphics Interchange Format was used as it allows an alpha channel to describe how transparent a particular pixel should be rendered, and in this way a more natural edge to the machine is portrayed (FIGURE 4.17).

FIGURE 4.17: The anaesthetic machine on a Billboard node, the use of the .gif format allows a smooth edge to be drawn as seen on the right.

There is always a trade-off between immersion and speed. Each object that is added will decrease the speed with which the graphics engine is capable of rendering the scene. In the case of the operating room and the anaesthetic machine, fast rendering of textured 2-dimensional surfaces achieves this aim.

4.3.3.2 Image Intensifier

Within the operating theatre x-ray images are used to guide the surgeon as to the position and orientation of the implants with respect to the bony anatomy of the patient. The development of the x-ray image intensifier (or C-arm) by Philips in 1955 and its introduction into orthopaedic surgery in the 1970s, allowed surgeons to visualise the position of the implants in real time. The image is visible on a monitor and there is no requirement for development of photographic film. The image intensifier works by converting x-rays to visible light through input screens, a microchannel plate and then a phosphor screen. It allows for a much lower dose of radiation to be used, however the downside is that only smaller sized images can be obtained, for example the proximal femur can be visualised, but not the entire length of the femur.

Although image intensifiers use less radiation, since their introduction there has been controversy over the amount of radiation exposure for the orthopaedic surgeon. Due to risk of radiation, such devices can legally only be operated by appropriately trained radiographers. Most radiographers use the ALARA (As Low As Reasonably Achievable) principle to govern the amount of radiation used. There appears to be a relationship between the amount of radiation exposure and the experience of both the surgeon and the radiographer, confounding variables include the complexity of the fracture (Giannoudis, McGuigan, & Shaw, 1998; Hafez, Smith, Matthews, Kalap, & Sherman, 2005).

The components of the image intensifier include the C-arm and the output display. The C-arm has 6 degrees of freedom. The base is on wheels allowing translation in one plane and the height of the C-arm can be adjusted allowing translation in the third dimension. The base can be angled around the room for 1 axis, and the C-arm pivots about 2 axes to provide the final degrees of freedom. Two x-ray images are taken in order to obtain a 3-dimensional understanding of the anatomy of the bone and location of surgical implants. Continuous fluoroscopy is seldom used within orthopaedic surgery due to the increased radiation exposure, rather single image radiographs are acquired. These images are most commonly an antero-posterior (AP) image (the x-rays pass from anterior to posterior within the patient, and a lateral view (with the x-rays passing laterally from one side of the patient to the other). These images are acquired by simply rotating the C-arm 90 degrees from the AP position to the lateral position as illustrated on FIGURE 4.18.

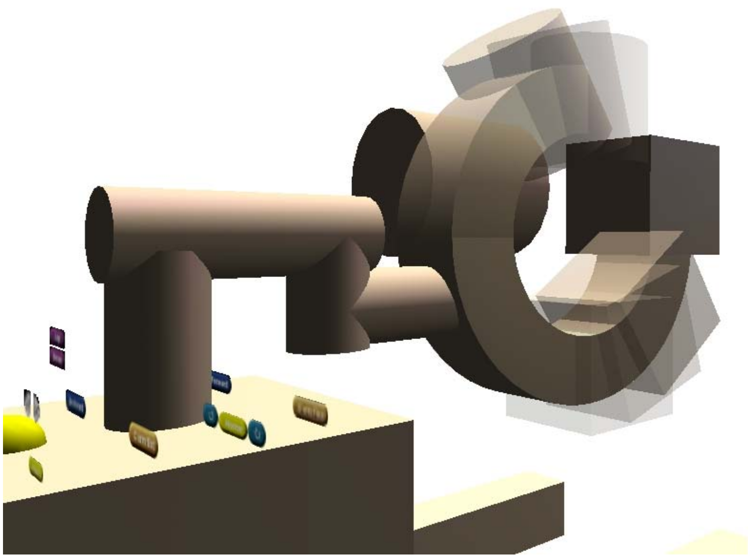

FIGURE 4.18: The image intensifier rotating from an AP position into the lateral position.

Given the number of degrees of freedom the image intensifier can move in, communication between surgeon and radiographer is important to the success of the procedure. It is interesting to note that for all the degrees of freedom within the machine, there are no common terms for movement at each of the joints. Often the surgeon knows in which angle to place the image intensifier, but without the ability to easily communicate this to the radiographer, a frustrating dialogue can ensue. Another method some surgeons use is to physically manhandle the machine into position. This is less than ideal given the expense of the image intensifier machine and the fulcrums around which the various joints of the C-arm operate. The combination of a relatively inexperienced radiographer and a relatively inexperienced surgeon means that neither member knows how to correct the position of the image intensifier to obtain the correctly angled x-ray image.

Another factor associated with the image intensifier is the fan nature of the beam. Objects which are closer to the x-ray source will appear more magnified than those closer to the receiver. The distance from the source to the receiver is just less than two and a half feet and the receiving plate is either 6 or 9 inches in diameter. In addition the operating table usually lies between the hip and the receiving plate, with the result that there is significant magnification of the image, and an inability to see a field greater than around 6 inches. This means that it is relatively impossible to assess accurately the overall angulation of long bone fractures. For this reason, in procedures such as casting of mid-shaft tibial fractures, long leg views with a traditional x-ray machine are obtained.

The virtual image intensifier has been modelled as a separate object within the virtual operating room. It can be positioned with 6 degrees of freedom. The articulations are placed at the same points as those of a real image intensifier. The image intensifier can be translated about on the operating floor, and the angle altered to manoeuvre around obstacles such as the non-affected limb. The C arm can be raised and lowered. The C arm pivots around 2 axes. Finally the image acquired can be rotated around to provide the surgeon with a view showing anterior to the top of the screen.

In real life, the radiographer unlocks a lever and physically angles the C-arm to adjust the image obtained. Within the simulator, clicking buttons on a console achieves the same purpose. The VRML implementation of this relies on TouchSensors to receive input from the user. Translation of the image intensifier is achieved by simply increasing or decreasing the translation component of the image intensifier. Rotation of the image intensifier is achieved by adjusting the revolving the whole image intensifier about the global y axis.

Raising or lowering the C arm is achieved by translating the C-arm in the global y direction. Rotation of the C arm in the final 2 axes is centred about a point midway between the x-ray source and receiver. The image obtained can be rotated around the axis orthogonal to the receiver plate.

In order to render the virtual x-ray a VRML Viewpoint node is placed within the x-ray source limb of the C-arm. A script receives the input from all of the various TouchSensors, and adjusts the corresponding angle or translation within the simulator, with the result that the x-ray source is adjusted and in turn the Viewpoint position and orientation is adjusted.

When the 'acquire image' button is pressed a virtual x-ray image is produced. This image is achieved by removing radiolucent objects such as skin and the operating table from the scene-graph. Then the alpha-value (degree of transparency) of the femur and pelvis is adjusted to 'see through' the bone. As can be seen in FIGURE 4.14 the colour of the bone is adjusted accordingly to create the appearance of bones viewed with x-rays, and the surgical implants are rendered as completely white (due to metal being completely radio-opaque). In order to obscure objects lying outside of the field of view, a virtual shutter is drawn when the virtual image is taken. This also encompasses a black box where the base of the C-arm would lie.

As mentioned previously communication between radiographer and surgeon is an important contributor to the success of the procedure. While designing labels for the buttons which move the various parts of the image intensifier, research was conducted into the correct terms for these movements. It came as somewhat of a surprise to find that there is no official terminology. Following discussions with senior radiographers, radiologists and surgeons appropriate terms from anatomy and common usage were used to describe these movements, namely Forward/Backward, Left/Right and Up/Down for translation of the image intensifier, Wig/Wag for rotation of the base of the intensifier, Flexion/Extension for rotation of the C-arm about its neck, and Lateral Flexion for rotation orthogonal to this, and finally Clockwise/Anticlockwise for rotation of the image in the plane of the receiver.

As described earlier, x-rays fan out from the source and fall on the receiving plate, essentially magnifying the size of objects closer to the source. By placing the Viewpoint node at the source and specifying the correct angle for the field of view, the browser calculates size with respect to distance, and automatically renders an appropriate image. As in real life, raising the height of the C-arm results in decreasing the magnification. The result of this is that more of the proximal femur can be visualised.

Due to the limited size and resolution of current computer screens, it is not possible to render the simulated x-ray view at the same time as the operative view. However in a way this does mimic real life, whereby the surgeon generally has to shift their eyes from the operative view to analyse the x-ray image. Within the simulator the x-ray image is seen while the mouse button is clicked and held.

Within surgery the image intensifier is placed in the correct position, and then a sequence of 2 orthogonal images are taken. This is to visualise 3 dimensionally the relation between the bone and the implant and to assess whether the fracture has been reduced anatomically. These images are generally an antero-posterior (AP) and a true cross-table lateral x-ray view (FIGURE 4.19). The design of the C-arm is such that usually these can be achieved by simply flexing/extending the C-arm about this axis. Although this sounds very simple, this manoeuvre usually takes around 30 seconds to achieve. This is mostly due to communication between the surgeon, radiographer and scrub nurse, as well as the requirement to shift surgical drapes to ensure maintenance of sterility. Within the simulator the trainee can simply click buttons between "lateral" and "AP" to view these different x-rays. When the surgeon needs the image intensifier to move distally to view the screw-holes, the image intensifier has to be shifted down the shaft of the femur, and this obviously takes some further time.

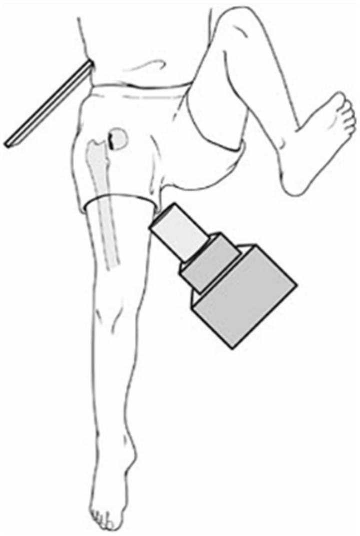

FIGURE 4.19: The position for a lateral view of the hip, with the unaffected hip and knee flexed to 90 degrees, and the beam aimed perpendicular to the femoral neck. From Fig 38-5 (Rockwood, Green, Heckman, & Bucholz, 2001)

4.3.3.3 Traction table

For most fractures about the hip, the patient is placed on a radiolucent operating table which enables traction to be applied to the limb with the fracture. This table has a flat part which lies underneath the patient's torso and head, and outriggers for the patients lower limbs. The non affected limb is usually held either abducted, or flexed and abducted, to allow the image intensifier to be focussed on the patients fractured hip. The foot of the affected limb is wrapped in stockinette and held within a boot. Traction is then applied to this limb. A padded post placed in the perineal region prevents the patient from sliding distally when traction is applied. Several different levers are adjusted physically to shift the patient's foot, and hence move the distal femoral fragment with respect to the proximal fragment including the head. The traction part of the table can be adjusted to manoeuvre the limb in all 6 degrees of freedom.

Within the simulator the traction table comprises 2 parts; the first consisting of the torso-support and non-affected limb extension piece, and the second part comprising the affected limb extension bar. The limb extension bar also houses the 'traction console' (FIGURE 4.12). The process of making the trainee move around a virtual traction device to alter each of these levers would make the simulator unnecessarily complicated, and indeed most traction tables have slightly different arrangements of levers. Therefore, there are simple buttons to push which adjust the traction in each degree of freedom, altering the position of the distal fragment of the fracture, and hence allowing reduction of the fracture. Each of the rotations and translations has their centre of rotation at the centre of the femoral head. This approximates the real life geometries about which the various components of the traction table moves.

Commonly the trainee needs the traction adjusted once they have started operating, either because the reduction has been lost, or to allow compression at the fracture site, rather than distraction. The ability of the trainee to communicate clearly and concisely with the theatre staff is beneficial to the progress of the procedure. As in the case of the image intensifier, development of the simulator meant that labels for each of the buttons had to be produced, and there were not many common terms in usage. Consequently labels taken from anatomical descriptions were used, specifically Flexion/Extension which is achieved by raising or lowering the foot off the ground, Abduction/Adduction achieved by swinging the leg away from the midline, Internal/External rotation of the foot, and finally Distraction/Impaction pulls or pushes the limb in the direction governed by each of these rotations. By having clear button descriptions on the simulator, trainees are more likely to use a common descriptor when asking other theatre staff to change the traction. In addition the frequent changes in theatre staff mean that a certain amount of pointing and non-succinct communication will still occur.

The skin of the lower limb is modelled as a separate object from that of the torso. Consequently the potential exists for a cleavage plane between these objects to be visible. However the anatomical constraints of positioning the limb mean that this potential for detracting visualization is avoided. In addition a virtual drape similar to the Redi-Drape® Ultra Vertical Isolation Drape (Biomet, Indiana, USA) is carefully positioned such that it does not contact or collide with the upper limb (FIGURE 4.20). These features have avoided the requirement for introducing contact into the simulator, as simulating contact is computationally expensive.

FIGURE 4.20: The blue Redi-Drape® type dressing radiates away from the operative field, thereby avoiding the need to introduce contact.

4.3.3.4 Implants

Surgical implants for fracture fixation include guide-wires, cannulated screws, cortical screws, and the sliding cannulated screw and plate. These implants are made of either titanium or stainless steel and are completely radio-opaque on x-ray. Within the procedure the hole will be drilled, and then a depth gauge or the length of drill within the bone is used to select the appropriate length of screw. Within the simulator the drill length is used to identify the correct screw. Thence a screw or wire of the requested length is created and placed. The creation of the implant at the time of request obviates the need to model and render a large number of different screw lengths, which would slow the frame-rate.

Guide-wires are 2mm diameter stainless steel wires which are held within a wire-driver or drill, and driven into the bone. Having ensured they are in the correct place and angled appropriately, a reamer and tap is then placed over the top of these wires to enlarge the hole within the femur and prepare for the cannulated lag screw. This screw is then placed over the guide-wire and tightened into position, following which the guide-wire is removed.

The Dynamic Hip Screw (DHS) is one of the implants used to fix fractured neck of femurs. It is manufactured by Synthes (Davos, Switzerland). It consists of a 6.5mm cannulated lag screw which sits within a barrel mounted on a side-plate. The lag screw is placed within the femoral head. The shank of the screw has cut-outs which fit within the barrel part of the side-plate, thus the screw is able to slide within the barrel, but is unable to rotate. This sliding occurs as the patient starts mobilising and impacts the fracture, and aids in fracture healing. In some thin patients the shank of the screw can irritate the soft tissues on the lateral aspect of the femur, and may be removed if the fracture has fully united. The side-plate also has holes which allow cortical screws to be placed and fix the plate to the shaft of the femur. This impaction aids in fracture healing. This impaction is demonstrated in FIGURE 4.21

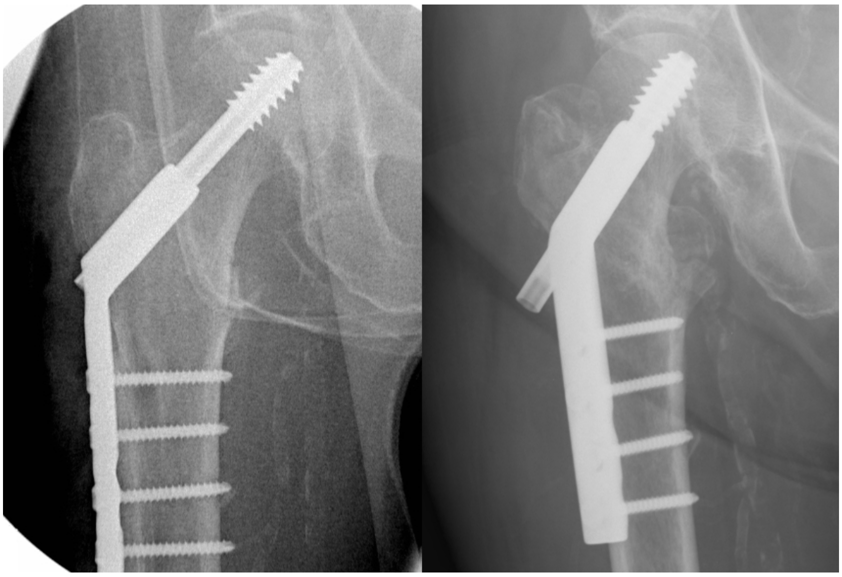

FIGURE 4.21: An intertrochanteric fracture, (a) intraoperatively, and (b) several months later, showing impaction of the fracture and sliding of the screw down the barrel of the plate.

Screws come in a range of sizes for a number of indications. The lag screw for the DHS is a 6.5mm shank cannulated screw. As this screw is significantly larger in diameter than the guide-wire some of the holes from incorrectly placed wires will be filled by the final lag screw. Other screws are 4.5mm cannulated screws which are sometimes used for hip fractures, but more commonly used for fixing slipped cannulated femoral epiphyses, as will be discussed in Chapter 6. Finally uncannulated 3.5mm screws are used for holding the side-plate of the DHS against the femoral shaft.

FIGURE 4.22: The virtual DHS implant showing plate, lag screw and cortical screws.

4.3.4 The Procedure of DHS fixation

The steps within the procedure of DHS fixation of hip fractures can be summarised as reduction of the fracture, placement of an appropriate skin incision, selecting the correct entry point, identifying the correct trajectory and length for the guide-wire, reaming over the guide-wire and placing the DHS lag screw and side plate, and finally filling the cortical screws to attach the plate to the shaft of the femur. The instruction manual describing how to perform the virtual operation can be found in Appendix B. The surgical technicalities involved in these steps, together with methods used to simulate these steps will now be described.

4.3.4.1 Fracture Reduction

A key learning point within the operation is how to reduce the fracture anatomically. With the apprentice style method of learning, most seniors will demonstrate how to reduce the fracture, and the junior sees the result of the reduction, without necessarily understanding the method the senior has used to achieve this result. The skill of reducing the fracture is based on a certain amount of intuition as to the position of the fracture, and which plane needs to be adjusted to correct the deformity. This is hard to communicate in words, and often the trainee is left to learn this by trial and error.

Understanding how the fracture is mal-aligned is based on correct interpretation of the orthogonal x-ray images. In addition understanding which movements of the traction table can be seen most easily on each of the AP or lateral x-ray images aids this understanding. Thus abducting or adducting the limb will not alter the appearance on the lateral x-ray, but will make significant changes to the AP x-ray. To a certain extent the effect of each of these movements relies on a true AP and lateral x-ray being acquired. If the C-arm is angled slightly oblique, then the appearance alters on both the AP or lateral x-rays. For ease of use, the virtual image intensifier has suggested views, which mimic what a junior radiographer might supply. While these views are close to the correct AP or lateral planes, especially for the first procedures, as the fractures become more complex and require further manipulation, the trainee has to adjust the position of the image intensifier. In reality when the fracture is perfectly aligned, a fracture line can still be seen on x-ray, however in the first version of the simulator the bone will look perfect if anatomically reduced, with obvious resultant feedback to the trainee that they have achieved this first step. While this is worthwhile for training, for further evaluation as to how successful trainees are at assessing the quality or acceptability of their reduction, the bone should never appear perfectly anatomical even when perfectly reduced.

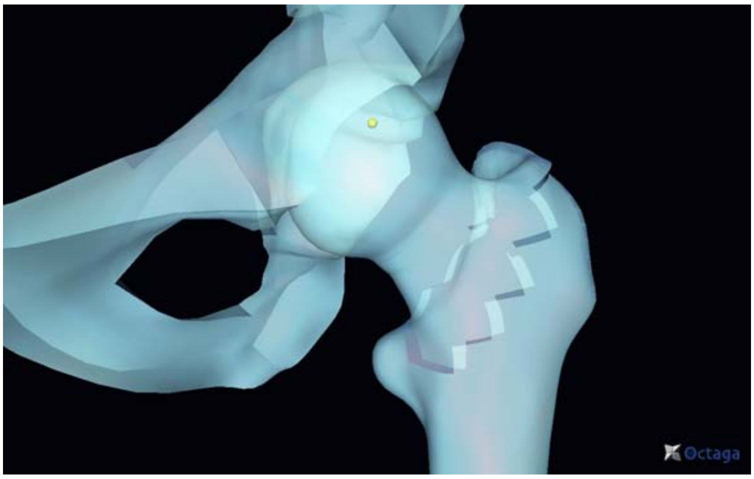

FIGURE 4.23: Virtual AP x-ray showing an intertrochanteric fracture

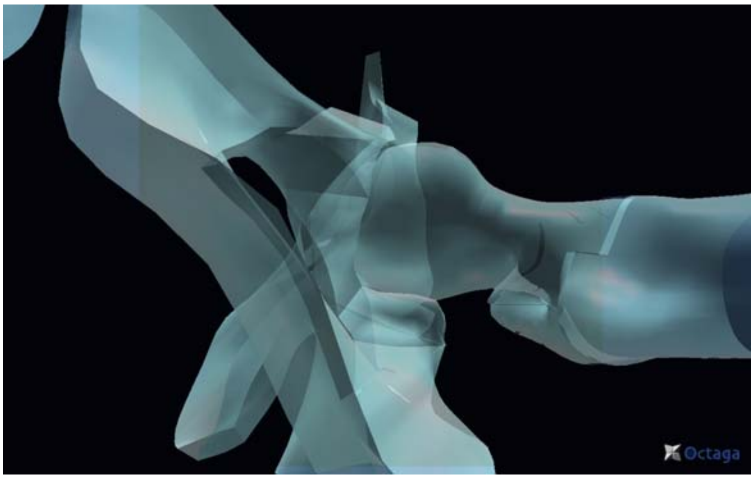

FIGURE 4.24: Virtual lateral x-ray showing an intertrochanteric fracture.

The ability to use trial and error to see the effect of various positions of the traction table on the reduction does not exist within training. Reasons for this include the risk of radiation exposure, the risk of complications from the anaesthetic the longer it takes to operate on the patient, the opportunity cost of tying up an operating theatre while a trainee practices, and the trainee not wanting to embarrass themselves by showing they do not actually understand the effect which altering the traction in different ways affects the x-ray appearance. By allowing each of these movements to be performed separately, and with the ability to check the image intensifier view after each adjustment of the traction, the simulator can teach the trainee this understanding.

4.3.4.2 Incision

Having reduced the fracture to their satisfaction, the trainee prepares to operate. The first step is 'prepping' the skin with an antiseptic solution like iodine. Then a Redi-Drape™ sterile drape is applied. This is a large plastic sheet, hung from supports, which divides the operating room in half; the image intensifier is in the non-sterile part, and the surgeon is on the sterile side. The centre of this sheet has a yellow adhesive rectangular segment which is placed over the proximal thigh. An incision is then made through the yellow segment of the Red-Drape™ drape and the underlying skin. Subcutaneous fat is incised, followed by the iliotibial tract, the underlying vastus lateralis muscle is then reflected using an osteotome, and finally the lateral aspect of the shaft of the femur is visualised.

Obviously the placement and size of the incision govern the extent to which the trainee can visualize the femur. The placement of this incision is determined by palpating the protuberance of the greater trochanter. Many trainees start their incision too proximally, with the result that when they are placing the plate, the incision often needs to be extended distally to allow the plate to be placed on the femoral shaft. Awareness that the incision needs to be centred over the plate, not the entry point of the lag screw would improve this placement. Anatomically by incising more proximally within the iliotibial tract, more tendinous fibres of the gluteus maximus and tensor fascia latae muscles are compromised. The compromise of these fibres may slow the recovery of the patient, as gluteus maximus is the major muscle involved in arising from the seated position, and tensor fasciae latae is used to maintain posture while standing.

Within the simulator the skin incision is made through a yellow panel representing the Redi-Drape™ type sterile guard. This VRML material node of this panel has a reduced alpha value, which makes the panel somewhat transparent and hence allows the femur to be slightly visualized.

Slight visualization of the femur is an approximation for the palpation of the greater trochanter of the femur, which would normally guide the placement of the incision (FIGURE 4.25).

FIGURE 4.25: The Redi-Drape™ type dressing is opaque allowing slight visualisation of the femoral shaft, though difficult to appreciate in printed version.

The skin incision is made by dragging a virtual scalpel across this yellow panel, and hence indicating the left and right margins of the wound. Then the skin edges are retracted (FIGURE 4.26). From the edges of this incision, a muscle layer is created. The muscle layer is in the shape of a funnel, with the shaft of the femur in the depth of the wound. A larger incision means that a larger funnel is rendered and a greater extent of the femoral shaft may be seen.

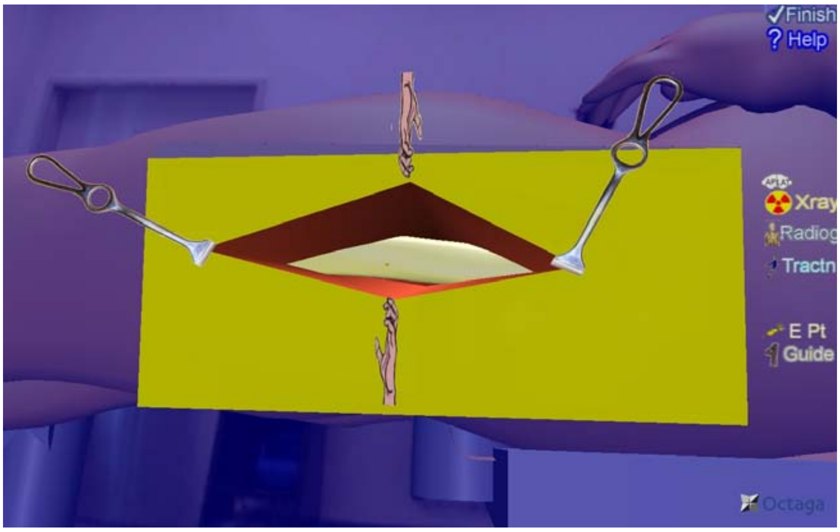

FIGURE 4.26: Following the incision, retractors hold the skin edges apart, these can be adjusted as required.

The skin incision can be adjusted at any stage of the procedure. This incision is made on a 2-dimensional object to reduce the computational load, and thus avoid the need to calculate cuts through polygonal or tetrahedral meshes as described by Bielser et al (Bielser, Maiwald, & Gross, 1999). This simplification allows for fast calculation. Altering any of the retractors thus requires a simple re-draw of the yellow panel and underlying muscle.

4.3.4.3 Selection of entry-point for guide-wire

Having incised the skin and elevated the vastus lateralis off the shaft of the femur, the surgeon then selects the entry point for a guide-wire. A guide-wire is then inserted into the femur using either a cordless or air-powered drill. A 135^0drill guide is used to help determine the correct angulation of this guide-wire to the femoral shaft. The guide is pushed against the lateral aspect of the femur. The 135^0 angle matches the angle between the femoral shaft and the femoral neck. The guide-wire is positioned on lateral aspect of the femoral shaft, and an AP x-ray is taken to guide placement in the superior/inferior plane. A lateral x-ray is not useful at this point as the x-ray is centred on the femoral head and the entry point will not be visible. Thus rather than relying on x-ray guidance, the surgeon estimates the correct anterior and posterior entry point based on the available view of the femoral shaft. Once this is thought to be acceptable the guide-wire can be advanced and seen on the lateral x-ray.

Within the simulator the surgeon clicks on the femur visible within the wound to select this entry point. This point can be checked using the image intensifier in the AP, but as in real life the entry point of the wire is just not visible on the lateral. It is possible to change the entry point at any time during the procedure.

4.3.4.4 Drill angulation

The angulation of the guide-wire is assessed by the interpretation of the x-ray images. Often the guide-wire must be advanced into the bone to fully identify where it would end up if advanced completely. If this angle is identified as being incorrect, the guide-wire must be withdrawn, the angle changed, advanced again and then checked on the x-ray image. Once the correct trajectory is obtained, the guide-wire is advanced until it reaches the subcortical bone (around 5mm short of the articular cartilage).

Within the simulator, the trainee clicks to select the entry point and the 135^0 guide is then drawn. This guide has a number of holes within it, so that as the guide and guide-wire are angled it is possible to ensure that this side-plate of the DHS implant will lie flush with the femoral shaft. The angle of the guide-wire is altered by clicking and dragging the guide-wire to the estimated correct trajectory and checked on the x-ray image.

Earlier versions of the simulator had four buttons to adjust the drill trajectory, with simple Up, Down, Left and Right buttons (FIGURE 4.27). By breaking the movement down into these simple 1 degree of freedom movements, the trainee is forced to channel their thinking, such that the position on the AP x-ray will guide only the movement of the hand in the superior/inferior direction. The appreciation of the correspondence of superior/inferior direction being visible only on AP x-ray is something which junior trainees acquire, but often this is implicitly learnt rather than explicitly taught. Later versions of the simulator removed these buttons and the adjustment of the guide-wire was by click and dragging. This latter option means that unless enough attention to detail is paid, it is possible to adjust the guide-wire in both directions at once, and complicate the manoeuvres. The first experiment, described in Chapter 5 used the four button method, while the slipped capital femoral epiphysis experiment described in Chapter 6 used the click and drag method.

FIGURE 4.27: The buttons used to control the guide-wire angulation in the early experiment.

Pushing buttons with a mouse or clicking and dragging is not a completely intuitive interface for angling a drill. A haptic device with a drill handle would obviously be of great benefit, however incorporation of a haptic device is computationally more expensive. Also when holding a drill attached to a haptic device it is not intuitive to use the drill to push a separate button within the simulator to take an x-ray. Another potential avenue to explore would be the introduction of a 3D mouse, although this is a reasonably inexpensive hardware item, there are no such mice found on current hospital computers. The use of haptics has already been described in detail within Chapter 2 and thus will not be described further here.

The rotation of the guide-plate onto the shaft is achieved by clicking and dragging this plate to the correct position.

The guide-wire is advanced into the femur by sliding a button on the control panel, simulating drilling the guide-wire into the bone. This is accompanied by a realistic drilling sound. The drill depth is displayed, and the trainee then checks this appearance on the virtual x-ray. Should this appearance be unsatisfactory the trainee will withdraw the guide-wire to alter the trajectory, the simulator will log the depth the wire was inserted, and a faint drill-hole will be added which is visible on the x-ray (FIGURE 4.28). The position of this mistaken guide-wire, the total length of incorrect drilling, and the number of times the guide-wire drill is withdrawn is recorded automatically by the simulator. This is discussed further later in this chapter.

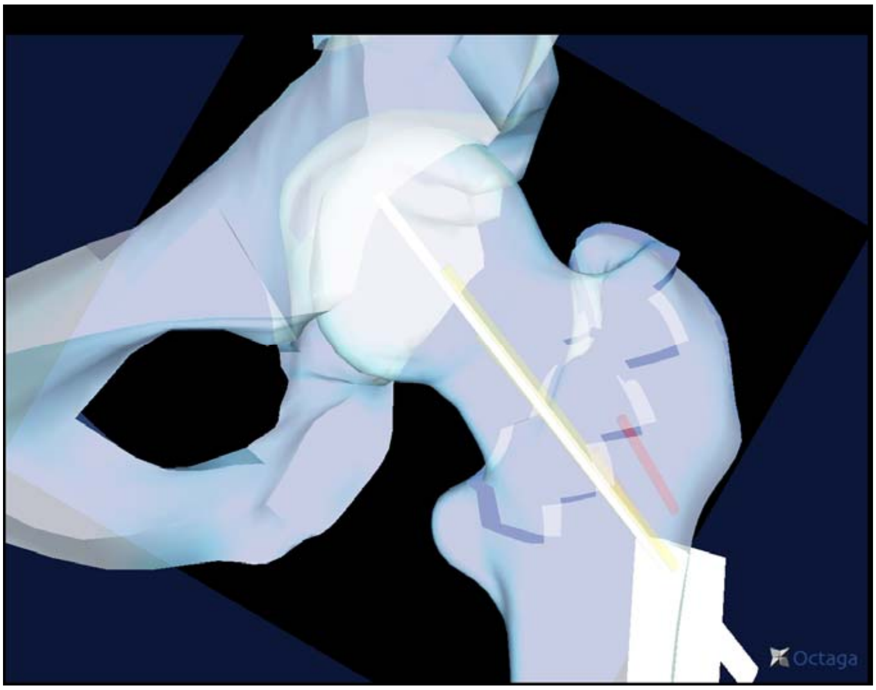

FIGURE 4.28: Mistakenly placed guide-holes are visible as coloured drill-tracks on this virtual x-ray. The first drill-track is red, the second is orange, and the third is yellow.

4.3.4.5 Implant insertion and plate positioning

During the procedure, an angle guide is used to aid the surgeon in approximating the 135-degree angle between lag screw and plate. This ensures that when the guide hole is drilled and lag screw inserted, the plate will lie flush with the shaft of the femur. Due to the convexity of the lateral surface of the greater trochanter, changing the entry point in the superior or inferior direction will also change the angle of the plate in the superior/inferior plane, such that a new entry point does not merely translate the guide-wire, but also changes its trajectory. In the virtual world contact between the guide-plate and the femur cannot be detected. As a result, the trainee does not know whether the plate is positioned proud of the femur, or indeed lies within the femur. By depicting the guide-plate with guide-holes within it, the trainee can see when the femoral surface of the guide-plate contacts the femur. This highlights to the trainee the impact the curvature of the greater trochanter has on the trajectory of the lag screw.

Although the implant is produced with barrel/plate angles of between 130-150^0, many hospitals only stock the 135^o plate. Thus for simplicity the simulator only models the 135^0 DHS plate.

4.3.4.6 Placement of anti-rotation wires

Basicervical fractures have been shown to rotate when the triple reamer has been used to prepare the femur (Mills & Horne, 1989). This is due to the increased torque of the reamer compared with the guide-wire. In order to prevent this from happening an anti-rotation wire or screw is placed prior to reaming. To ensure that this training point is covered the simulator requires the trainee to place an antirotation wire or screw when a subcapital fracture is operated on, otherwise the femoral head rotates, and the position is lost.

4.3.5 Score-sheet

As described earlier one of the key features which distinguishes a virtual reality simulator from other forms of training exercises is the ability to obtain objective scores about the performance of the simulated task. FIGURE 4.29 shows the score-sheet which is given to the trainee at the conclusion of the procedure. This section describes these various scores which the Bon*e*doc simulator generates, the method of generation, and the implications for learning and assessment.

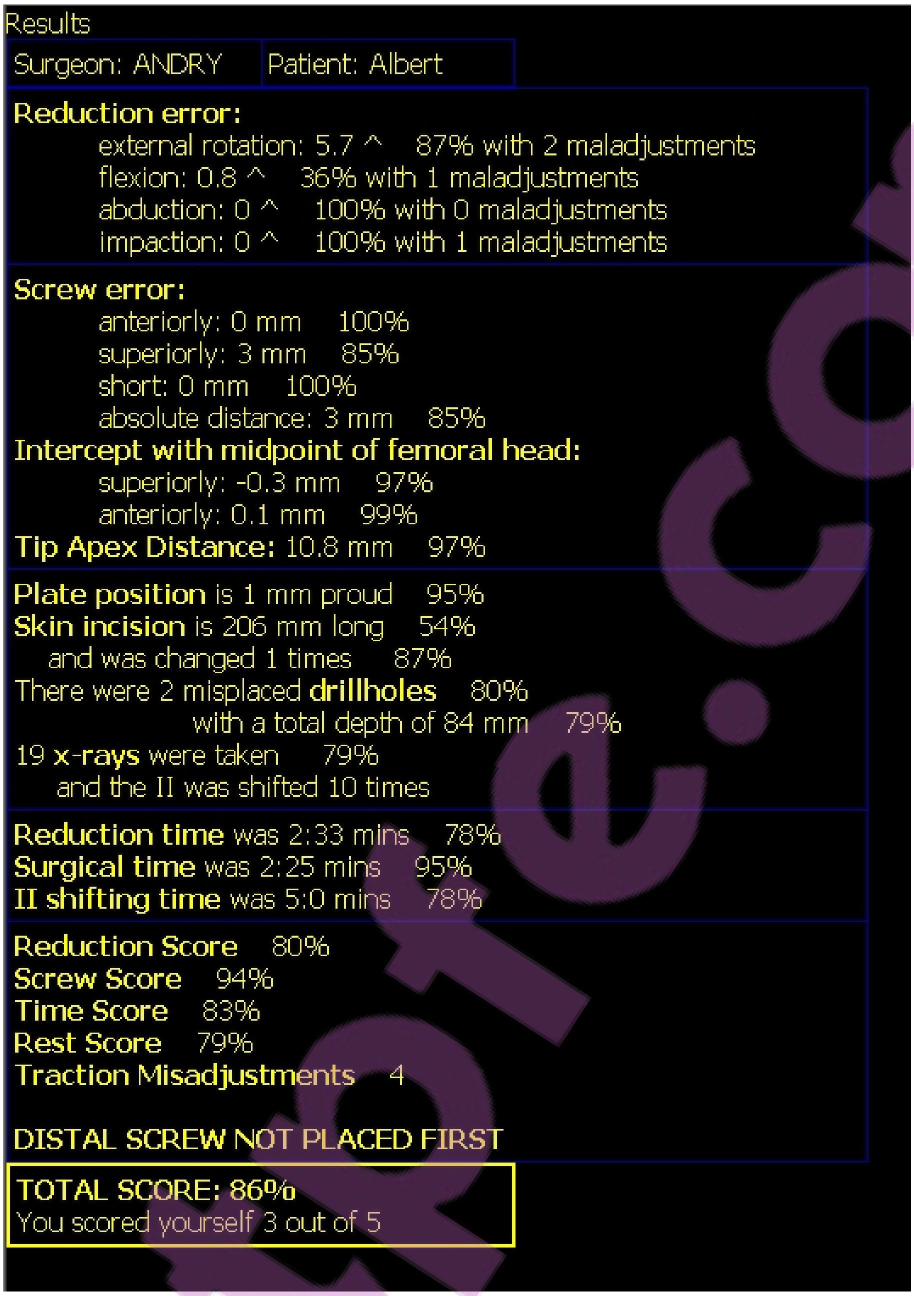

FIGURE 4.29: Objective score-sheet produced for trainees with the results uploaded to server.

4.3.5.1 *Relevance to clinical practice*

There are many different results which the simulator could measure, however it was elected to restrict the amount of data to those parameters which mimic the results which could be obtained in a real operating theatre. Trainees can compare their performance on the simulator using the same goals they are trying to achieve in the real world, such as accuracy of reduction and accuracy of screw placement. Within the real world obtaining these measures absolutely would require further imaging of the patient with means such as a CT scan. CT scans would then have to be further processed to calculate each of the measurements of fracture reduction. This may entail a CT scanogram to delineate the femoral axis correctly. Similarly, obtaining each of the displacements of the screw from the ideal spot would require a fair amount of manipulation of the images. While this is all potentially achievable the effort required is fairly considerable. In this regard the ability of the simulator to generate each of these measurements in real time is a distinct advantage to the trainee. From the training committee's viewpoint, the ability to compare all trainees on the same procedure on the same virtual patient has further advantages as will be discussed in Chapter 6.

Simulators such as the Mist VR laparoscopic simulator make extensive use of economy of movement or timing as markers of performance. This amount of movement has been shown to decrease as surgeons become proficient on the simulator (Hamstra & Dubrowski, 2005; Woodrum et al., 2006), however provided the surgeon does not damage structures in the real world, more "forceps waving" does not necessarily make for a worse procedure. Thus having trained on a simulator, and utilizing this feedback a trainee may adapt a different style of operating which may not be their natural method.

4.3.5.2 3 Dimensional view at conclusion

The information which individual x-rays provide can at times be somewhat deceptive. The two supposed orthogonal views provided by the image intensifier must be correctly interpreted by the surgeon to avoid placing the compression screw out of position and lying within the hip joint. Consequences of this error result in iatrogenic arthritis and chondrolysis. However the ability of the surgeon to estimate the 3D location of this screw is variable, as will be discussed in Chapter 6 concerning a SCFE screw.

At the conclusion of the virtual operation all the skin and muscles are stripped away and the bone is turned translucent in order to facilitate learning of how x-rays can be misleading. By navigating around this 'virtual dissection' the trainee is able to assess the extent to which the misplaced guide-wires may be filled by the final lag screw, as well as ascertain visually how close to the femoral neck of articular surface the various guide-wires or lag screw came. An example of the view is shown in the FIGURE 4.30.

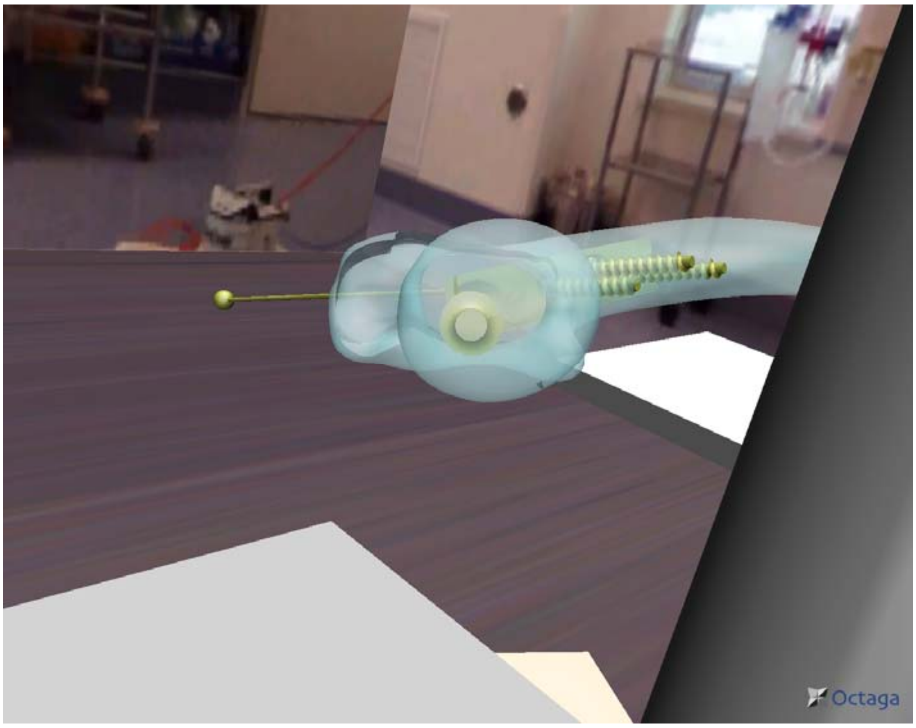

FIGURE 4.30: "Virtual dissection" showing position of implant in 3-dimensions.

4.3.5.3 Accuracy of reduction

The quality of the reduction is defined by how close to the normal anatomical position the fractured limb is placed. This is defined with respect to each of the planes, namely flexion/extension, abduction/adduction, internal/external rotation and distraction/impaction. All of these axes are measured in degrees, apart from the last where distraction/impaction is measured in mm. To encourage the trainees to interpret the x-ray appearance and adjust the traction accordingly different configurations of the traction table are prescribed for each individual patient. This configuration is set for each patient by deciding the degree to which the trainee will need to adjust the traction in each of these axes and then placing the femoral head or proximal fragment in the appropriate position and orientation. During the simulation the trainee must then match the position of the distal fragment to the proximal fragment in order to perfectly reduce the fracture.

Normally following fracture of the femoral neck, the lower limb lies in external rotation and is shortened (or impacted), this is thought to be because the pull of the iliacus and psoas muscles on the lesser trochanter occurs without the normal constraints of the 'hinge type' arrangement of the femoral neck. Therefore in order to reduce the fracture, traction is applied to the limb, followed by internal rotation. Although this is normally the situation, it does not happen in all cases, and consequently the trainee still needs to interpret the appearances of the x-ray in response to the attempts at reduction.

If the bone ends of the fracture site are examined it is possible to see that these are not smooth surfaces but indeed have matching teeth like projections. With any impaction at the fracture site these surfaces will interdigitate to some extent. The result of this interdigitation is that rotation of the distal fragment will cause the proximal fragment to rotate as well. To avoid this problem the fracture is distracted before correcting the deformity.

Currently within the simulator the position of the femoral head is kept constant, and altering the position of the distal fragment by adjusting the traction does not affect this position. A more advanced method would be to require the trainee to apply traction before applying any rotations at the fracture site. The simulator has been written such that the position of the head is identified and tracked, thus all that is needed to allow rotation of the head is a simple script to determine whether the head should rotate (as there is not enough distraction applied). This has not currently been included in the simulator as there is not currently literature to support this modelling, and it was felt that rather than fabricate relationships which might not be accurate, it was better to maintain simplicity. Another consequence of having a proximal fragment which moves is that a trainee might spend a large amount of time ‘chasing their tail’ as they try to get the fracture reduced. This is somewhat akin to what happens in theatre.

The computation of how well the fracture has been reduced occurs through a number of steps. Firstly the position and orientation in each of the axes for the proximal and distal femoral fragments is obtained. Then a simple subtraction of the angle in each axis produces the extent to which the trainee has failed to reduce the fracture in that axis. Similarly simple subtraction of the distances of impaction/distraction produces the amount of error in that plane. This is discussed further in Appendix E.

Piloting of the software showed two different styles of using the simulator to reduce the fracture, a group of high school students with large amounts of computer gaming experience used a large number of x-rays and basically reduced the fracture through trial and error. A group of middle aged engineers thought at length before adjusting the traction and took a more judicious number of x-rays. In order to capture these different styles, the number of times the traction is adjusted in error (that is adjustments which produce worsening angulation at the fracture site) is recorded.

4.3.5.4 Accuracy of screw placement

Achieving accuracy in screw placement is one of the most important tasks for trainees. The ability to achieve this is dependant on correct interpretation of the x-rays, as already discussed. The ideal placement of the screw lies parallel with the femoral neck, situated centrally within the head to lie

5mm short of the articular surface (Baumgaertner & Solberg, 1997; Schumpelick & Jantzen, 1955). The simulator provides feedback on how this aspect was performed by defining this accuracy in each of the relevant planes. These planes are the superior/inferior plane, the anterior/posterior plane and short/long. The short/long plane is defined as lying along the line parallel to the centre of the femoral head and neck, with the zero point being 5mm short of the articular surface. The superior/inferior plane was defined by the intersection of this plane and one passing through the epicondyles of the distal femur. The anterior/posterior plane was defined as lying orthogonal to these other planes. (FIGURE 4.31). Although there are a number of different coordinate systems which could be used, the system described was selected on the basis of ease of interpretation by the trainees with the particular task of DHS fixation of femoral neck fractures.

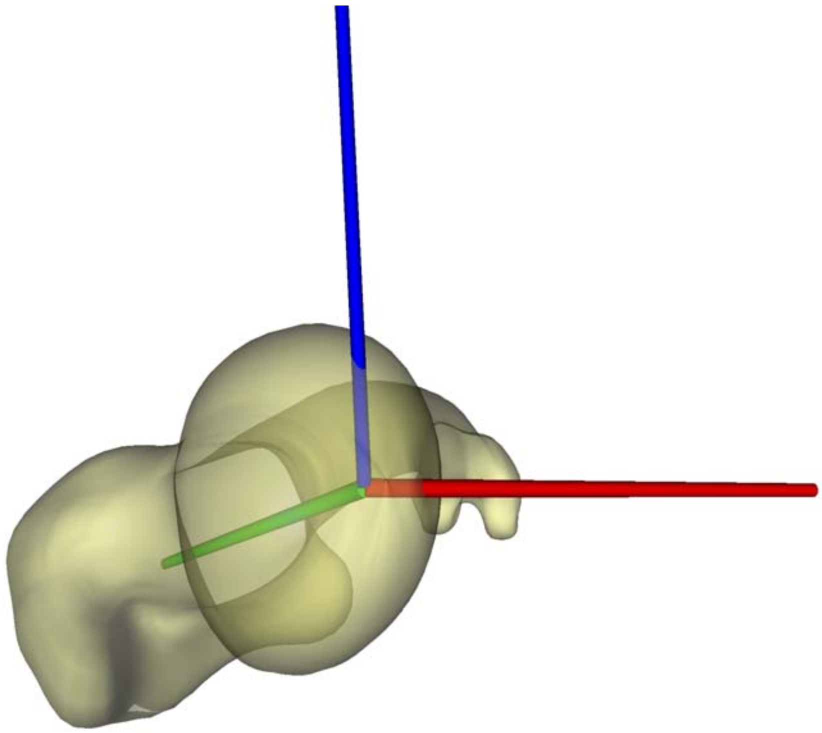

FIGURE 4.31: Femoral axes, the green bar is in line with the femoral head and neck, the red bar is in same plane as the femoral condyles and the blue bar is orthogonal to these.

Calculation of this accuracy relies on describing the distance between two points (namely the ideal spot, and the tip of the lag screw), in each of three axes. However calculation of the location of these points requires taking into account various transformations. For the screw-tip these include, location of entry-point, angulation and length of screw placement, (this vector is a subordinate of the position of the femur as determined by the traction position). The position of the ideal spot is determined by its position within the femoral head, as well as the transformation of the femoral head within the acetabulum. These calculations are described further in Appendix D.

One of the methods described in the literature to assess the accuracy of screw placement is the point at which the screw intersects with a plane placed on the midpoint of the femoral head (Parker, 1992). This has lead to the description of aiming "centre centre" being in the centre of the femoral head on both AP and lateral x-rays. This is a measurement which is relatively easy to obtain on post operative x-rays. Consequently this measurement has been included within the score-sheet of the simulator, with results given in mm deviation from the centre in both anterior/posterior and superior/inferior planes. The calculation of this intersection between the line of the screw and the plane of the centre of the femoral head is described in further detail in Appendix E.

The tip-apex distance as described by Baumgaetner et al (Baumgaertner, Curtin, Lindskog, & Keggi, 1995), is a simple method of describing the position of the screw within the head, suitable for use with standard x-rays. This is defined within this paper as "*the sum of the distance, in millimetres, from the tip of the lag screw to the apex of the femoral head, as measured on an antero-posterior radiograph and that distance as measured on a lateral radiograph, after correction has been made for magnification*". To facilitate integration of the simulator with clinical practice the tip-apex distances are also calculated within the simulator, this is described within Appendix D. As this is calculated rather than measured, there is no requirement to allow for magnification from the image intensifier.

4.3.5.5 Mistakes

Each time a trainee drills a hole into the femur a 2mm diameter defect is created within the bone. This has the potential to act as seed-point for propagation of a fracture (Canale et al., 1994). The risk of fracture increases as the number of mistakes which are made, as well as the depth of drilling. When the trainee identifies that the guide-wire they have placed is not perfectly positioned, a decision has to be made as to whether the risk of placing the screw slightly out of position, is greater than the risk of creating more damage to the femur by drilling another hole.

The simulator records both the number of mistakes which are made as well as the depth of bone which is drilled. Within later versions of the simulator the operating styles of trainees was analysed in more detail, by also plotting the displacement of the misplaced screw in two dimensions, this will be discussed in Chapter 6.

4.3.5.6 Positioning of the plate

Positioning of the plate flush with the shaft of the femur is an important part of the task. This positioning is determined to the greatest extent by the angle of the screw in the superior/inferior direction, though the position of the entry point and the anterior/posterior angulation is important as well. If the plate is positioned in such a way that it sits proud of the shaft, then by fixing the plate under tension with the screws will lead to one of two outcomes, either the fracture will be forced into a valgus angulation (which some proponents advise for some fractures (Pajarinen, Lindahl, Savolainen, Michelsson, & Hirvensalo, 2004), or if the bone is not sufficiently strong, then the screws will cut out, and the implant fail. For this reason the simulator measures how snugly the plate fits against the shaft of the femur.

4.3.5.7 Skin Incision

As discussed above, correct placement of the skin incision will dramatically affect the ease with which the rest of the procedure is carried out. A smaller incision will expose the patient to less chance of bleeding as well as less injury to adjacent tissue, however this must be balanced by the risk of placing the implant in the wrong position due to inadequate views of the appropriate landmarks.

The simulator records both the length of the incision and the number of times the incision is changed. This latter recording is because often less attention is paid by trainees when extending incisions, and often less appropriate instruments are used for this extension, such as scissors or the diathermy.

4.3.5.8 X-ray Dosage

The risks of radiation exposure are thought to be dose-dependant. Although the image intensifier uses less radiation than conventional radiographs, there is still significant exposure to trainees and indeed other members of the surgical team when the image intensifier is used (Dewey, George, & Gray, 2005; Singer, 2005). The risk of radiation needs to be balanced with the risk of inadvertent hip joint penetration, which can even be fatal (Mishra et al., 2002; Mueller, Jahnich, & Butler-Manuel, 2005).

Each time a new virtual x-ray image is requested, the total number of images taken is tallied. The actual amount of radiation used per view is determined by a number of variables, including the size of the patient. In addition the position of the image intensifier with respect to the surgical team and therefore the amount of scatter makes a significant difference to the radiation exposure to the team. For this reason the simulator merely states the number of x-rays taken, rather than giving the dose in Sieverts or grays. This reporting of radiation exposure is in keeping with the ALARA principle as described in Chapter 2.

4.3.5.9 Time

Recording of the time taken for surgery is important for a number of reasons, from the patient's view-point the risks of both anaesthetic and surgical complications are correlated with increased time. These complications may result from blood loss and hypothermia.

The simulator records three times, firstly the time taken to reduce the fracture, secondly the time to operate, and the time taken to alter the position of the image intensifier from AP to lateral positions. In order to ascribe the length of time added to each procedure by each change of position, the real time taken within theatre was recorded during all changes of position in three operations. The average was 30 seconds. This 30 seconds includes the time taken for the radiographer to receive the instruction, and adjust the position of the intensifier, the time taken for the scrub nurse or trainee to adjust the surgical drapes to maintain sterility, and finally to acquire the image.

4.3.5.10 Overall Percentages

A method of encouraging usage of the simulator is to create competition between or within trainees. To encourage competition the simulator provides easily comparable results. Thus for many of the parameters described above, a percentage score is given. This percentage score is based on an arbitrary range from absolute failure to a perfect score.

Additional penalties are also imposed for behaviours which have been associated with poorer clinical outcome within the literature, for example the percentage score for the intercept of the screw with the midpoint of the femoral head in the superior plane is calculated as

$$\text{Intercept}_{\text{Sup}}(\%) = \frac{(20\text{- }(\mathbf{2*}\text{intercept}))}{20} * 100$$ if the screw lies superiorly, but

$$\text{Intercept}_{\text{Sup}}(\%) = \frac{(20\text{- }(\text{intercept}))}{20} * 100$$ if the screw lies inferiorly.

This is on the basis that error in the superior plane is twice as bad as error inferiorly, and a screw placed 20mm away from the midpoint would get a score of zero.

The overall score is based on addition of component scores weighted according to the estimated impact of these components on the overall outcome to the patient, whereby screw score contributes 60%, anatomical reduction 15%, time 10%, and others 15%. Obviously this is an arbitrary definition, and as such has its faults, however the advantage of providing a single score at the end of the procedure provides the subjects with an easy means of comparison. From the patient's viewpoint, a well placed screw in reduced fracture will give the best chance of fracture healing, however factors such as length of incision and time taken will impact on things such as risk of infection, requirement for blood transfusion and risk of anaesthetic complications. The x-ray dosage is probably more important from the surgical team's viewpoint.

4.4 Face Validity

Face validity measures how closely a simulator replicates the task it is designed to reproduce. In order to measure the face validity of the Bon*e*doc simulator, a questionnaire was written enquiring about various aspects of the simulator. The questionnaire is included in Appendix A. The questions were adapted from the survey of orthopaedic surgeons on attitudes to simulation described in Chapter 3. A 5cm visual analogue scale was used to quantify responses from "Disagree Strongly" to "Agree Strongly". This was measured using a digital calliper and converted to a 10-point score. Further comments were also sought using free text box replies.

Subjects for the study were recruited from the local tertiary level hospital. The subjects ranged from 4th year medical students on their orthopaedic ward attachment, to registrars and orthopaedic surgeons. The subjects completed the six operative scenarios on the virtual simulator, and then filled in the questionnaire.

4.4.1 Results:

4.4.1.1 Demographics:

Ten subjects, (aged 20 to 50, 9 male, one female) completed the questionnaire. There were three medical students, four junior trainees and three senior trainees or orthopaedic surgeons. None of the subjects had had previous exposure to a VR simulator. The study participants scored themselves on their level of computing knowledge with a median score of 3.9. Despite this relatively low score every subject said that they accessed the internet every day.

4.4.1.2 Simulator performance:

The study participants' evaluations of the simulator performance are summarized in FIGURE 4.32. Most study participants felt that the simulator provided a realistic view of the operation (median score 8.2/10), and that the 3-D view provided was all that is required (median score 7.8/10). The simulator appeared to be robust with most study participants disagreeing with the statement that the simulator was too slow or crashed (median score 1.7/10). The simulator interface seemed intuitive with all participants disagreeing with the statement that the interface was too complex (median score 1.8/10). The scenarios were perceived as being different enough (median score 8.1/10).

4.4.1.3 Tasks and Requirements of the Simulator:

The study participants' evaluations of the tasks and requirements of the simulator are summarised in FIGURE 4.32. The subjects were split on whether haptics (force feedback) should be incorporated with the majority disagreeing with this statement (median score 4.6/10). They all agreed that the simulator provided feedback on their performance (8.7/10) and it allowed them to practice angulation / spatial orientation of the guide-wire and implant (8.5/10). However, most subjects disagreed with the statement that the simulator enables revision of anatomy (4.7/10). Most subjects also disagreed with the statement that the simulator allowed minimally invasive surgery practice (score 3.8/10).

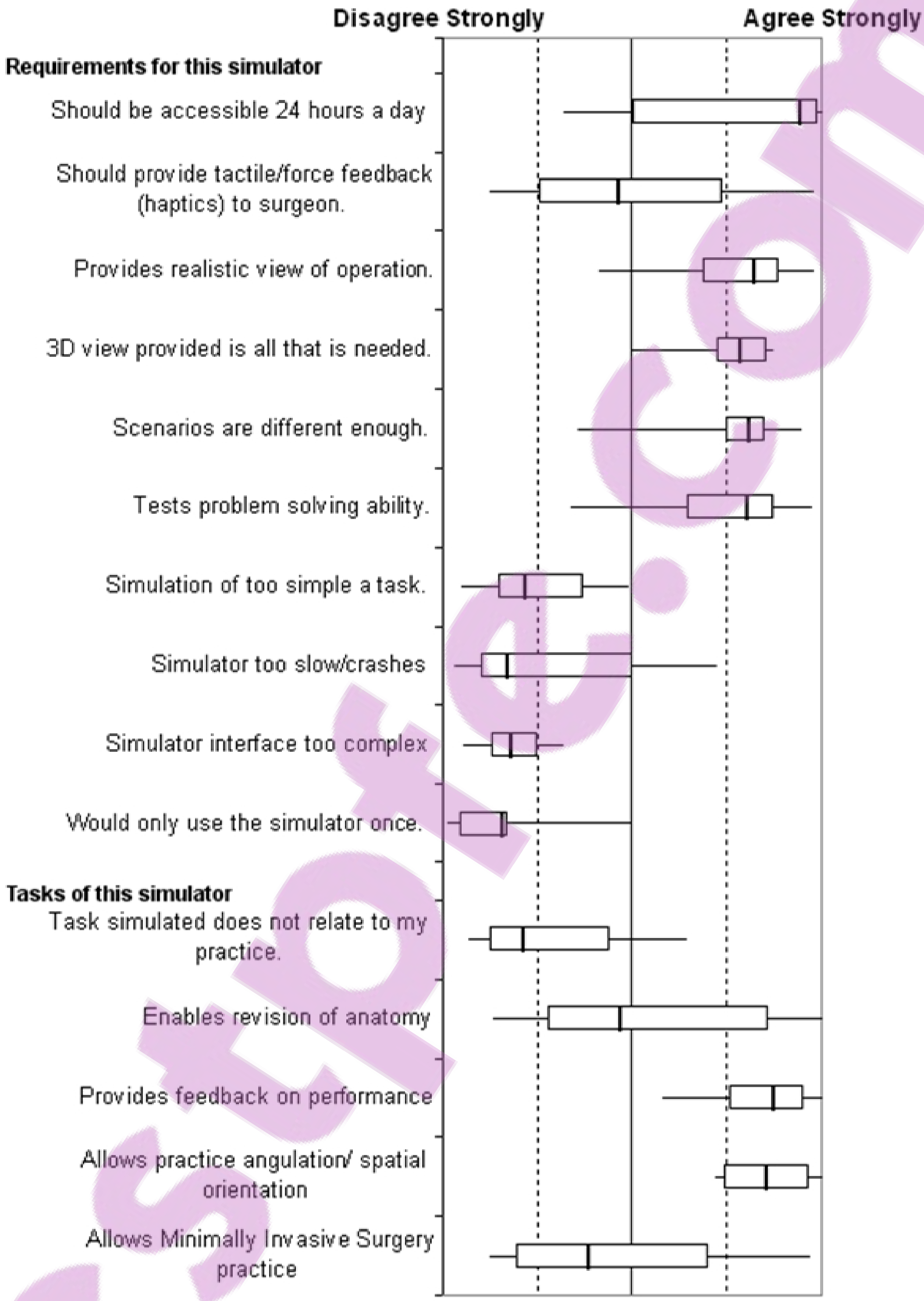

FIGURE 4.32: Study participants' evaluations of the simulator performance presented as box plots showing range, 25-75% range (box) and median score (solid line).

4.4.1.4 Free Text Box Comments:

The free text box replies were all positive, with comments from the different skill level groups reflecting their respective viewpoints. Examples of what the medical students thought that the simulator included *"Exposure of different cases that is otherwise unavailable to students"*, *"As a student who has recently seen several hip operations, this was an extremely fun and interesting experience to 'do' the procedures myself"* and *"Easy to use, excellent graphic and design (v accurate) good tool for med student to familiarize w surgery beforehand"*, and *"I believe this was an extremely useful experience for myself as a student and would highly recommend it"*

Junior trainees thought the most useful aspects of the simulator were the ability to *"practice reduction of the fracture"*, *"practicing picturing angles and entry points"* and gain understanding of *"The level of perfection required when attempting different anatomies"*.

Senior trainees and surgeons reflected on the simulator as a whole, stating that it provided an *"Excellent simulation of real life operation"*, *"Realistic simulator of all surgical steps necessary to complete surgery satisfactorily", "Extremely valuable tool for junior medical staff"* and the capability of *"Being able to see screw placement in the bone in 3D once operation was finished."*

4.4.2 Discussion

The overall question which this questionnaire sought to answer was to assess the degree to which Bon*e*doc has face validity. Nine of the ten participants felt that the simulator provided a realistic view of the operation and that the 3D view provided was all that was required. This is a testament to the fact that although there is no bleeding incorporated within the simulator and no stereovision goggles were used, the participants were still able to immerse themselves in the simulator enough to feel that the experience was giving them enough information necessary to the procedure.

A key factor as to whether a simulator will be used more than once is whether there are enough different experiences to make it worthwhile to repeat the procedure. A common behaviour is that as soon as an operative procedure has been performed often enough such that the trainee feels they know the procedure they will stop practicing and seek new challenges. The participants found that the operative scenarios were different enough, even though only sliding screw fixation of femoral neck fractures was simulated. This is most likely because the fracture patterns were different and the anatomy of the femurs was different. This affects the entry points and the angles required to achieve a good result.

The previous survey on attitudes within the orthopaedic surgical community found that most orthopaedic surgeons and trainees thought that the incorporation of haptics (touch feedback) should be a necessary requirement for a simulator (Blyth, Anderson, & Stott, 2006). However, the respondents in that survey had had no practical experience with orthopaedic simulators. By contrast, the feedback following use of this simulator (which does not include haptics) indicates that more than half of the study participants felt that haptics were not needed; the senior trainees were more likely to feel that haptics did not need to be incorporated. Thus, it is important for the developers of simulators to ensure that the financial and computational investment of incorporating haptics into a simulator is justified.

One valuable aspect of the current simulator is its ability to provide formative feedback to the trainee across a wide range of measures, such as quality of fracture reduction, feedback on incision length, misplaced drill holes, the accuracy of lag screw placement and position of the plate, number of x-rays taken, and the time taken to complete the surgery. The current simulator also has the ability to pinpoint exactly where in space the lag screw is placed, independent of any potential distortion from the image intensifier views. Thus, the exact 3-dimensional location of the screw head, and also the 'true' quality of fracture reduction can be demonstrated to the user. This was featured in the free text box feedback. The participants in this study felt that the simulator provided valuable feedback on their performance, a task that our previous survey of orthopaedic surgeons and trainees had scored highly as a necessary feature of a simulator (Blyth et al., 2006). This may be because the current simulator can provide results of the operation in objective terms, with which surgeons and trainees can readily identify, such as deviation of the lag-screw from the correct position measured in millimetres. This measurement contrasts to the proximate data such as economy of movement, which haptic-based simulators tend to provide (Gallagher et al., 2005).

The practice of a skill over several days has been shown to be a critical factor improving learning and retention of motor sequence tasks (Savion-Lemieux & Penhune, 2005). A major goal of the current work was thus to create a simulator that could be used frequently and be accessible from a surgical trainee's own work environment. This helps facilitate repetitive practice at times convenient to the trainee. Further discussion on how the simulator was used at various times of the day will be discussed in Chapter 5. Feedback from the study participants shows the value of providing a simulator which is accessible at all times Accessibility of the simulator allows a surgical trainee to use the simulator at any time to refine surgical techniques such as progressively reducing the length of the incision, and gaining experience on the more limited view that this affords. The trainee can also experiment to see exactly how a certain change in guide-wire angulation will affect the result, or take a multitude of x-rays.

The participants in this study felt that the simulator was successful in modelling real-life events in the operating room indicating good face validity without the incorporation of computationally intensive touch feed-back (haptics). The simulator is now ready to be tested for construct validity.

4.5 Summary

This chapter has described the components of the virtual operating suite which have been designed and developed in order to simulate the procedure of sliding screw and plate fixation of femoral neck fractures. The technical considerations of how these objects were created are included together with descriptions of the reasons why these are important for simulating this procedure. One of the novel aspects of this simulator is the way that the results which trainees receive from the simulator match results which are possible and valuable to obtain in real life. These results are not obtained routinely due to the cost and labour intensive nature of acquisition. Also there is risk to the patient from having a CT. The chapter concludes with a study seeking to address the question of how well the simulator achieves its goal of reproducing the necessary operative steps for this procedure. This study showed that users of the simulator felt it did reproduce these steps. The results were compared and contrasted with the survey of the wider orthopaedic community. The ability to practice angulations was found to be a key feature of the simulator, which is in agreement with the previous survey, while other features such as the requirement for haptics were seen as less important. Having shown that at face value the simulator appears to resemble the important features of the operation, the next step is to assess whether the simulator is able to discriminate between users with different levels of real world operative experience.

C h a p t e r   5

5 CONSTRUCT VALIDITY

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

5.1 Introduction

There are three factors which a simulator needs to fulfil before it will be adopted by regulatory bodies, these are cost, relevance to real world performance, and validity. The uptake of simulators within the airline industry is probably more to do with overall regulation by bodies such as the Federal Aviation Authority than demand from pilots themselves. This regulatory requirement has driven the necessary funding to improve the simulators fidelity, which in turn improves the attractiveness of a simulator for pilots. As flight simulators were being developed in the world wars, there was a paucity of aircraft for pilots to train on, thus there was a desire to acquire the necessary skills in other ways.

However within the health sector, generally there exists a plethora of patients awaiting surgery, and as such there is no attractiveness to a lower fidelity experience. Before any regulatory body requires simulation as part of its accreditation, a simulator must be proven to be a valid trainer or assessment tool. Without a regulatory body to drive its use, the uptake of a simulator will depend less on validity, and more on cost, relevance to the real world, and perhaps most on the appeal of the simulator. An essay by Guest (Guest et al., 2001) explores the role of experience and expertise, proposing that performance is dependent on both the time spent and quality of the practise. Practise is effective when it is directed towards improvement rather than maintenance of skill, is at the appropriate level of difficulty, is informed by immediate feedback, and includes opportunities for repetition and correction. Within the realm of medical practice a widely accessible, fun VR simulation has the potential to allow this practise to occur. This chapter will describe how the Bon*e*doc simulator is attempting to achieve these goals.

Having developed the simulator to the stage where it was robust enough for use by non-experts, and provided enough realism, the simulator could be further validated. The next validation test which was applied to the simulator was that of construct validity. If the results from the simulator reflect surgical skill, then a suitable construct could be defined as those subjects with greater operating skill should perform better on the simulator than those with less skill. However currently there is no objective reliable measure of operative skill, and therefore a surrogate marker of surgical experience was chosen. The construct was thus defined as: "subjects with greater operating experience in the real world should perform better in the virtual environment, than those subjects with less real world operating experience". In addition the effect of experience with computers or computer gaming prowess on performance on virtual surgery simulation was examined.

5.2 Methods

5.2.1 Subjects:

Three groups of subjects with different amounts of orthopaedic exposure were voluntarily recruited. Ethics approval was granted for the study by the University of Auckland Human Participants Ethics Committee (Appendix H), and all subjects gave informed consent. Fourth year medical students (MS:n=6) on their first orthopaedic rotation had no operative experience. Basic trainees (BT:n=6) had a limited amount of experience with the operation. The highest skill level group consisted of either consultant surgeons, fellows or advanced trainees (AT:n=6), all having significant experience with the real world procedure.

5.2.2 Protocol:

Each subject was guided through the first operation by the principal researcher. Online and hard copy help was available for subsequent operations (Appendix B). Each subject completed 6 operations for sliding screw and plate fixation of femoral neck fracture, these operations were on different virtual patients named alphabetically Albert, Bob, Charles, Daniel, Earnest and Fredrick, with one of three different fracture types (either intertrochanteric, basicervical or subcapital) as described in Chapter 4.

The steps of the procedure which are simulated include placing the image intensifier appropriately to view the fracture, reduction of the fracture using the traction table, skin incision, identification of entry point, angulation and depth of a guide-wire over which a sliding screw is placed, and finally placement of the cortical screws holding the side-plate as described in Chapter 4. It is possible to place anti-rotation wires or screws, and subjects were penalised if these were required to maintain fracture position. Patients Charles and Fredrick had subcapital fractures and required either an anti-rotation wire or screw. All operations were performed on the left hip. As the simulator was available online, the virtual operations could be performed at any hour of the day.

5.2.3 Data acquisition:

During the virtual operation, various parameters were measured by the simulator. Following completion of the operation, the subjects self-assessed their performance, and could then view the fracture and implant position from any direction, and zoom in as necessary.

In addition objective feedback was provided, this included:-

- Fracture reduction error measured in degrees,
- Screw placement error in 3 planes,
- Positioning of the plate,
- Length of skin incision,
- Number of misplaced drill-holes.
- Number of radiographs acquired,
- Number of times the image intensifier was shifted from AP to lateral.
- Time taken to reduce fracture
- Surgical time
- Number of traction maladjustments (increasing the angulation of the fracture)

The methods and reasons for these measurements have been described in Chapter 4. This information together with the subject's code, virtual patient's name, time of surgery, and the subject's self-assessment were automatically uploaded into a database on a server.

5.2.4 Questionnaire:

Prior to commencing virtual operating, a single page questionnaire was completed to identify level of experience. The questionnaire is attached in Appendix A. This was divided into 5 sections, Demographics, Previous computer surgical simulation experience, Computer experience, DHS operative experience, and Computer access. This questionnaire comprised a combination of tick boxes, free text boxes and a visual analogue scale. The five centimetre analogue scale was used to quantify responses from "Complete Novice" to "Expert". This was measured using a ruler and converted to a 10 point score. The visual analogue scale allows a continuum of responses, thereby reducing the artificial distribution of positive and negative responses (MacCormick et al., 2002).

5.2.5 Data analysis:

The objective scores from the simulator were automatically uploaded into a database at the completion of each virtual operation, and the questionnaire responses were manually entered into the database. This database was subsequently imported into Statistical Analysis System (SAS 9.1) software (SAS Institute, Cary, North Carolina, U.S.A.) for analysis. Differences were tested for significance using the General Linear Mixed Model (SAS 9.1), a repeated measures analysis which models the correlation between repeated data from the same subject. Following statistical consultation, orthogonal contrasts were set up to test for both difference between medical students and trainees and also whether basic trainees differed from advanced trainees.

5.3 Results

5.3.1 Demographics and Experience:

There were 6 medical students (MS), 5 male and 1 female, with all aged but one aged less than 30 years. Their average frequency of playing computer games was fortnightly/monthly. Their self described level of computer knowledge ranged from 5.0-9.0/10 with an average of 6.6/10.None had previous experience with fixing a fractured NOF.

The 6 basic trainees (BT) were all male, aged between 25-40 years. Their average frequency of playing computer games was monthly/seldom. Their self described level of computer knowledge ranged from 1.4-8.0/10 with an average of 4.1/10. Their experience of fixing a fractured NOF ranged from twice weekly to monthly, with an average of weekly/fortnightly.

All 6 of the senior registrars / consultants (AT) were male, aged between 30-55 years. Their average frequency of playing computer games was monthly/seldom. Their self described level of computer knowledge ranged from 2.0-6.6/10 with an average of 4.2/10. Their experience of fixing a fractured NOF ranged from twice weekly to yearly, with an average of weekly.

	Age (Gender)	Operative Experience	Average Computer Knowledge (self-ascribed)
Medical Students	<30yrs (5 males,1 female)	None	6.6/10
Basic Trainees	25-40yrs (6 males)	<3 years	4.1/10
Advanced Trainees	30-55yrs (6 males)	>4 years	4.2/10

TABLE 5.1 Demographics of the three groups.

None of the subjects had had previous exposure to computer based surgical simulation.

The results from the simulator are divided into sections, namely fracture reduction, screw position, other operative values, times, and overall scores.

5.3.2 Fracture Reduction

There was no statistical difference in the final position of the fracture between the three groups, with the medical students and BTs scoring an average of 87% and the ATs scoring 85%. If the fracture was correctly reduced it looked anatomically perfect and the fracture line was not visible. Consequently subjects could spend as much time or effort as they liked to get the fracture anatomically reduced, though the simulator recorded this behaviour.

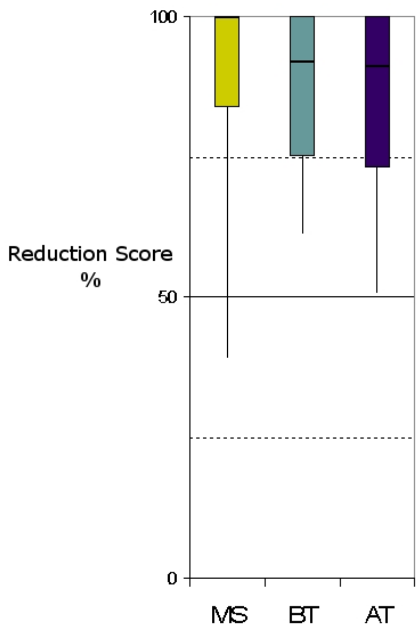

FIGURE 5.1: Boxplot of total reduction score for each group.

The medical students were more likely to adjust the traction in the wrong direction while trying to reduce the fracture. This occurred with a median of 19 maladjustments per operation (range 3 to 62). Basic trainees maladjusted the traction a median of 12.5 times (range 0 to 60), while the advanced trainees maladjusted the traction a median of 13.5 times per operation (range 0 to 100) (not significant) (FIGURE 5.2). The trainees accepted a minimal amount of displacement of the fractures, unlike the medical students, with a resultant statistically significant lower overall reduction score ($p<0.01$). The final fracture position accepted was within five degrees of anatomic for flexion/extension and seven degrees of anatomic for varus/valgus at the fracture site for all groups. Rotational malpositioning of up to 29 degrees were present, with the greatest rotation being present in the BT group.

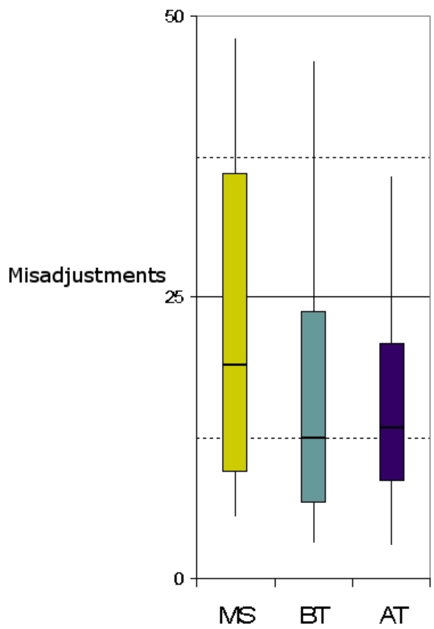

FIGURE 5.2: Boxplot showing total maladjustments for all operations between the three groups.

If the subject did not place an anti-rotation wire or screw before placing the definitive screw (in the case of subcapital fractures) then the fracture reduction was lost. This happened in a single operation in both med students and BTs but not the ATs.

5.3.3 Screw Position

Overall, there were fewer instances of clinically significant error in screw placement amongst the groups with more experience, with medical students breaching the cortex of the femoral head with the lag screw on 12 operations, the BTs on 6 operations, and the ATs on 2 operations ($p<0.01$ between MS and trainees, not significant between BT and ATs).

Calculating the distances of the lag screw from the screw-tip to the ideal spot in each of the three planes showed statistically significant differences between medical students and trainees, but not between advanced and basic trainees (FIGURE 5.3). In the anterior/posterior plane the medical students placed the screw a median of 4 mm posterior to the ideal spot, while the BTs and ATs were within 1mm of the correct plane ($p<0.01$ between MS and trainees). In the supero-inferior plane the medical students placed the screw with a median of 5mm superiorly, while the BTs placed it 4mm and the ATs placed it 3 mm from the ideal spot ($p<0.05$ between MS and trainees). The screws were placed around 1.5mm short of the ideal spot by the medical students and BTs while the ATs placed the screw around 1mm short (not significant).

With regard to the intercept of the screw from the midpoint of the femoral head, the ATs outperformed the medical students and BTs. The median for medical students was 3.4 mm superiorly and 4.9 mm posteriorly, BTs median was 1.75 mm superiorly and 1.25 mm posteriorly, while the ATs screws median intercept was 1.5mm superiorly and 0.9 mm posteriorly ($p<0.05$ superior direction and $p<0.01$ anterior direction for MS vs. trainees)(FIGURE 5.3).

The corrected Tip-Apex Distance (Baumgaertner et al., 1995) median (and range) was 18.66 mm (8 to 38) for medical students, 16.7 mm (7 to 36) for BTs and 14.2 mm (4 to 26) for ATs ($p<0.05$ between MS and trainees) (FIGURE 5.3).

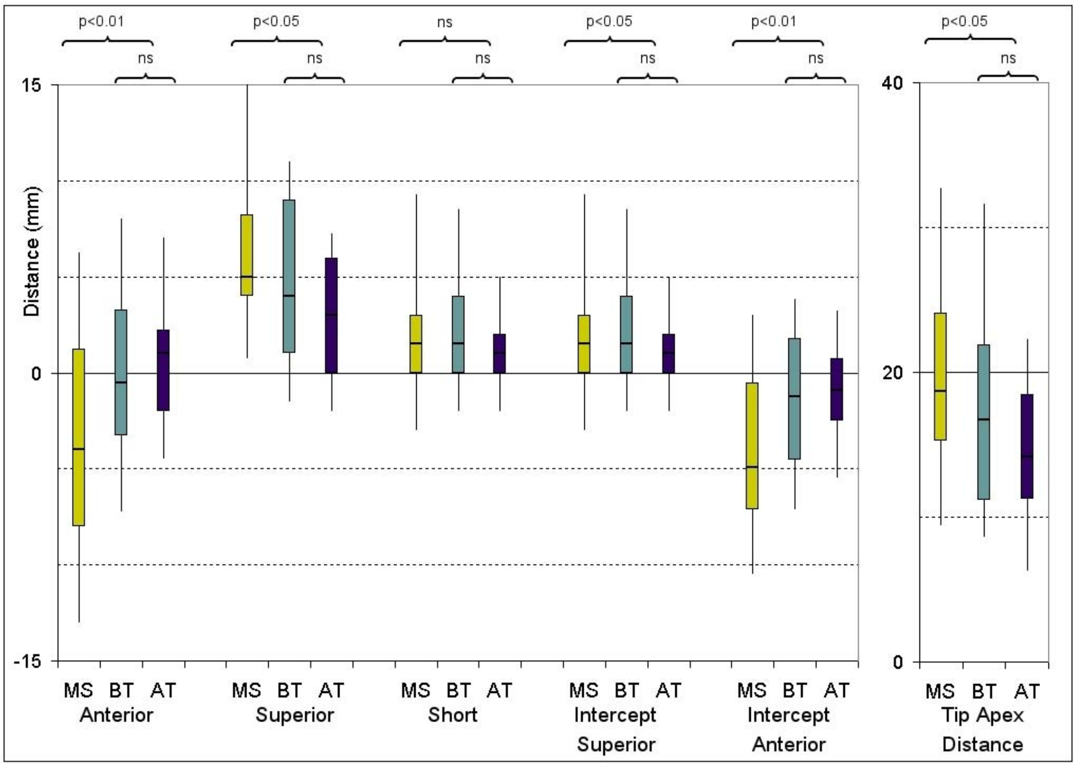

FIGURE 5.3: Boxplots of screw accuracy by plane, intercept and tip apex distance for each group.

5.3.4 Other aspects

Skin incision between the groups was variable, with results around 160mm for the med students and ATs and 140mm for the BTs($p<0.01$) (FIGURE 5.4), and all groups changing the incision length around once per procedure. All groups had an average of around 4 misplaced drill-holes per procedure.

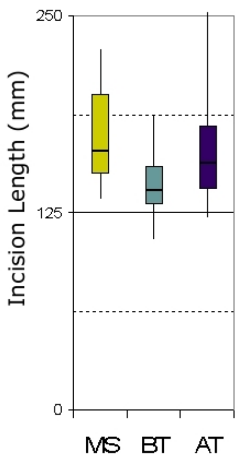

FIGURE 5.4: Boxplot showing incision length for each group.

Placement of the plate against the femoral cortex was performed best by the medical students, followed by the advanced trainees and finally the basic trainees. These results were significant with $p<0.01$ between both MS and trainees as well as between BTs and ATs.

The medical students took more x-ray images, around 71 per procedure, while the BTs and ATs were 45 and 51 respectively ($p<0.01$) (FIGURE 5.5). In addition the medical students shifted the II from the AP to lateral position 26 times, while the BTs shifted it 9.7 and the ATs around 20 times($p<0.01$ between both MS and trainees and between BTs and ATs).

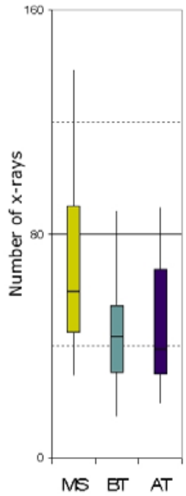

FIGURE 5.5: Boxplot showing the number of x-rays taken by each group.

5.3.5 Reduction and Surgical Time

The medical students took longest to reduce the fracture with a median time of 04:11 minutes. The ATs had a median of 3:04 minutes to reduce the fracture, while the BTs median was 02:40 minutes. Median surgical time was 09:32 minutes for medical students and 08:59 minutes for ATs while the BTs took 06:00 minutes.

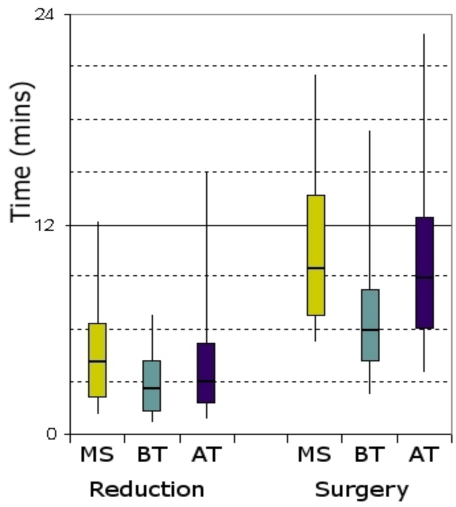

FIGURE 5.6: Boxplots showing the reduction time and surgical time for each group.

The amount of time spent shifting the Image intensifier from AP view to LAT view (around 30 secs per shift) would add around 13:23 mins to the med students, 10:11 mins to the ATs and 4:50 mins to the BTs.

The median time to complete the simulation was 14:56 minutes for the medical students, 09:31 minutes for the BTs and 13:13 minutes for the ATs. These times do not reflect the actual time it would take to perform the surgery within the real world, as it does not include the time taken for prepping the skin, the surgical approach to the femur, achieving haemostasis, reaming, using the depth gauge to measure screw lengths, filling the screws, and closing the wound at the conclusion. Importantly it does not also include the time taken for interactions with the scrub-nurse, such as communication, waiting for implants to be unpackaged, and the handling of the instruments. It would be expected that familiarity with the procedure would greatly increase the speed with which all of activities could occur, and thus in the real world the ATs should perform these aspects faster

5.3.6 Time of day

The simulator was accessible on-line, and thus the virtual operations took place at all hours of the day, with 20 of the 108 operations taking place after 8pm (FIGURE 5.7). There were insufficient data to analyse whether timing of the procedure impacted on the outcome of the procedure.

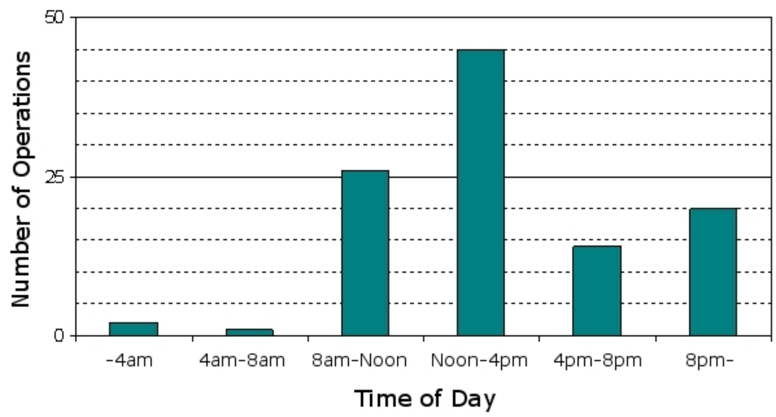

FIGURE 5.7: Frequency of operations by time of day for all groups.

5.3.7 Learning Curve

The learning curve for the simulator appears relatively shallow or non-existent, as seen on FIGURE 5.8, showing the range of accuracy (as absolute distance from ideal point) by patient for each group.

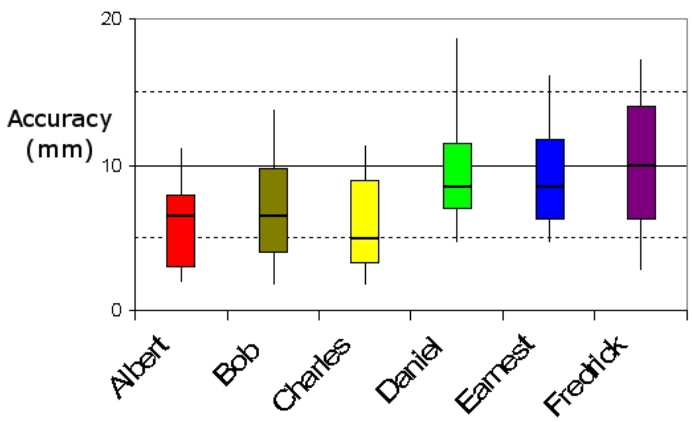

FIGURE 5.8: Boxplot showing the absolute screw accuracy for all groups by patient.

However as subjects gained experience with the simulator some efficiency was gained with regard to speed as can be seen on FIGURE 5.9, showing the surgical time by patient for each group.

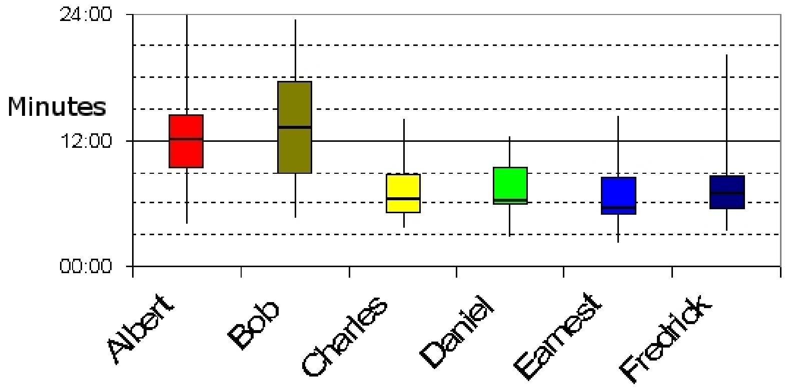

FIGURE 5.9: Boxplot showing the surgical time for all groups by patient.

5.3.8 Overall Score and Self Assessment

An overall score is calculated which provides a final single percentage on how the subject performed the operation, this includes scores for reduction, screw accuracy, time and other aspects. The ATs performed overall the best with an average score of 65.6%, while the BTs scored 58.8% and the medical students scored 44.2%. Kruskal-Wallis test has Chi-square of 15.185 with p of 0.001. Their self assessment reflects this to some extent with med students self scoring averages 1.8/5, BTs self-assessing 2.1/5 and ATs self assessing 2.4/5.

The highest score was an advanced trainee with an aggregate of 89%. His screw was placed 1mm out in each plane, the intercept was displaced 0.6mm inferiorly to the midpoint of the head, and 0mm superiorly. This was self-assessed as 4/5.

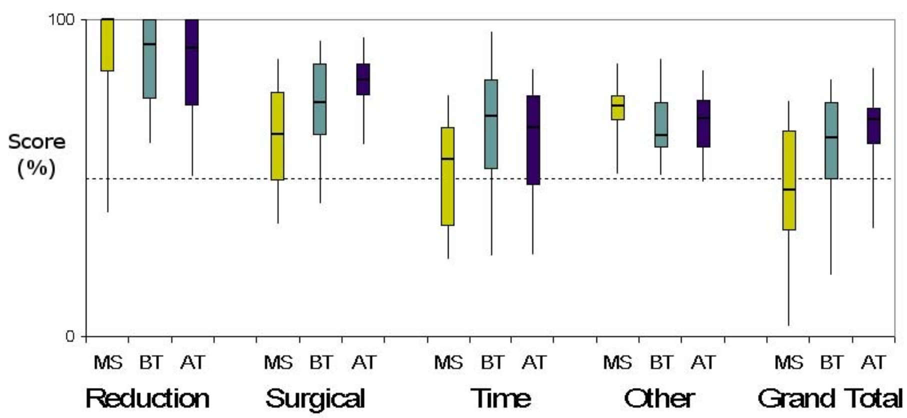

FIGURE 5.10: Boxplots showing the percentage scores for each group by component

5.4 Discussion

This study set out to test the construct that the Bon*e*doc Surgical simulator is capable of distinguishing virtual operative performance between 3 groups with different real operative experience. Differences were found between a number of variables such as screw placement, incision length and the number of x-rays taken. However the simulator was unable to find statistically significant differences between the basic and advanced trainees for most parameters, this may have been due to the relatively small number of trainees available within the institution, or other confounding variables which will be discussed.

5.4.1 OSATS vs. Virtual Reality Assessment of Technical Skill

The ability to identify individuals whose skills in a particular area need improvement, is vitally important for patient safety. As discussed earlier in Chapter 2, this assessment needs to be performed within a safety culture, otherwise individuals may feel threatened. The attitude towards this assessment will also be affected by the markedly influenced by these individuals impression of the validity of the assessment.

Within surgery the Objective Structured Assessment Of Technical Skill (OSATS) provides a means whereby the technical skills of a trainee are assessed rather than merely the knowledge base (Martin et al., 1997). Despite being proposed as early as 1971 in orthopaedics (Kopta, 1971) it is still used mostly within the research arena rather than surgical training. Although this assessment is seen as essential, problems of cost, personnel requirement, objectivity in marking and perhaps surgical relevance, have impeded its uptake. Virtual reality has the potential to deliver on a number of these aspects. This paper presents a further development of this concept which could be called Virtual Reality Assessment of Technical Skill.

Apart from simulation the aviation industry uses another tool called Line Operations Safety Audits (LOSA). These involve a pilot sitting in the cockpit and analysing each decision the pilot and flight crew makes. The evaluating pilot is not rated for the particular aircraft in which the audit is taking place, moreover it is the decision making which is analysed rather than pure aeronautical performance. In this regard it is similar to a black box, and perhaps suffers from a similar lack of reproducibility as OSATS, however the important part is the safety drive within the industry to ensure that these quality assurance measures are maintained rather than only relying on analysis from crash investigations (Helmreich & Merritt, 2000). If a pilot's score is too low, then they are expected to spend more time in the simulator in order to up-skill etc. Audits have been a large feature of surgical practice for some time, however auditing of procedures where no direct complication occurs is only just starting to take place, as discussed in Chapter 2. Measurement tools used within the aviation industry like Line Operations Safety Audits are used because the regulatory bodies or airlines have regulated that these procedures should be a requirement for ongoing certification.

5.4.2 Training Paradigms

The current paradigm of simulators and training rely on trainees attending workshops at specific times requiring them to leave the hospital environment, however the Bon*e*doc simulator allows the virtual procedures to be performed at any time of the day from any internet connected computer. Within this experiment 20/108 of the procedures took place after 8pm. The ability to conduct the experiment within working hours would be logistically more difficult as trainees frequently have interruptions to their normal schedule. These interruptions are for reasons such helping out in other clinics, covering for trainees who are sick, or performing surgery when there is a backlog within the operating theatres. The availability of a web-based simulator makes it more likely that trainees can seize the opportunity of training during downtimes while on call. Thus a simulator which is accessible 24 hours per day, 7 days per week has considerable potential.

Although there was not enough data to analyse the effect which time of day had on the virtual performance, there are examples in the literature which show that procedures performed outside of working hours are more prone to complications. This simulator has the ability to analyse the influence of time of day on outcome, without exposing patients to risk. There is most likely some variation in how well individuals are able to cope with factors such as lack of sleep, and the simulator has the ability to provide this information to individuals, this will be discussed in further detail in Chapter 7.

5.4.3 X-ray Exposure during Training

Image guided surgery currently relies mostly on the use of x-rays, rather than ultrasound or MRI. The concomitant risk of exposure to radiation is not completely documented, but there are concerns that trainees and surgeons may be exposing themselves and other members of the surgical team to harmful levels of radiation (Dewey et al., 2005; Giannoudis et al., 1998; Hafez et al., 2005). Even if most surgeons are not being exposed to excessive doses of radiation during their training and practice, very few trainees will practice on mannequins or models. Instead they acquire the skill of determining 3-Dimensional trajectory from 2 orthogonal x-rays on a living patient. This simulator provides an avenue for acquiring this skill without radiation exposure.

The medical students required the most virtual x-rays to complete the procedures. This corresponds to the increased radiation exposure found amongst junior trainees in the hospital environment (Giannoudis et al., 1998). The Bon*e*doc simulator allows juniors to develop skills in interpreting trajectories from x-ray images, without either exposure to radiation, or the cost of paying for the use of an image intensifier and a radiographer. Further studies are required to identify whether use of the Bon*e*doc simulator can enable this learning, or whether the trainee needs to have a physical drill to hold while practicing these angulations.

5.4.4 Aspects of Assessment

Within the real world there does not exist the possibility to compare performance between individuals because each operative case is different and consequently it is difficult to allow for the impact of this variation on outcome. In addition, measurement of outcomes such as position of screws is prone to inter and intra-observer variability (Heetveld, Raaymakers, van Walsum, Barei, & Steller, 2005). Chapter 6 will describe in more detail the ability of the simulator to make these comparisons.

Many simulators rely on parameters such as time and economy of movement to grade candidates on tasks. Certainly in some aspects, such as potential for infection, this may be of relevance however objective measures such as position of a screw have been proven clinically to determine the final outcome of a procedure (Baumgaertner & Solberg, 1997; Parker, 1992; Pervez, Parker, & Vowler, 2004; Thomas, 1991). It is for this reason that the Bon*e*doc simulator uses these real-world measurements in the feedback to the trainee.

The impact of computer skills / gaming experience on virtual performance was addressed by asking subjects the amount of time spent playing computer games, as well as their self-reported level of computer knowledge. Although this has previously been reported as having an impact on performance (Grantcharov, Bardram, Funch-Jensen, & Rosenberg, 2003) no statistically significant evidence of a relation between either gaming experience or computer knowledge was found. BTs had a small advantage of both increased computer expertise (relative to ATs) and increased operative skills (relative to medical students), this may have resulted in them performing faster than both groups, however final screw placement was worse than for ATs.

A study by Schijven et al showed surgeons were unable to estimate their own performance well on an endoscopic simulator (Schijven, Jakimowicz, & Schot, 2002). Within this study, there was little correlation between self-appraisal and total scores or other individual parameters. This finding is in contrast to studies such as that by Moorthy et al (Moorthy, Munz, Adams, Pandey, & Darzi, 2006), which showed that senior trainees had strong correlations between self assessment and expert ratings. It is possible that each subject judged their performance on different characteristics, as the question merely stated "How do you rate your performance?"

There did not appear to be much of a learning curve associated with driving the simulator, with no trend in the overall scores. Many experiments reported in the literature for simulators use more subjects, however they do not examine the effect of the learning curve, and look at the results of only 1 or 2 attempts of each task on the simulator (Bloom et al., 2003; Koch et al., 2007).

5.4.5 Objective Parameters from the simulator.

The main objective finding of this chapter is that ATs are able to place the dynamic screw more accurately within the femoral head. This has been shown to be one of the most important factors for success of the operation (Baumgaertner & Solberg, 1997; Parker, 1992; Pervez et al., 2004; Thomas, 1991). This result is dependant on interpretation of orthogonal images, and corresponding adjustment of entry point and trajectory, a skill which is almost unique to orthopaedic surgery. Currently there is no feasible method to practice and develop this skill outside the operating theatre, due to the hazards of radiation. It is in this arena that a simulator such as Bon*e*doc has the ability to provide the means to practise towards expertise, with immediate feedback and opportunities of repetition and correction (Guest et al., 2001). Baumgaertner et al (Baumgaertner et al., 1995), have described graphically a probability function between the Tip Apex Distance and probability of cut-out. From this we can calculate the probability of cut-out of the DHS screw if these screws were placed in real people as 16 in 1000 for the medical students, 14 in 1000 for the BTs and 9 in 1000 for the ATs.

The positioning of the plate on the femur was performed differently by the 3 groups, with the medical students performing best at this aspect. Adjusting the entry point also changes the trajectory of the screw due to the flare of the greater trochanter. If the plate does not lie against the femur, an undue amount of strain may be placed on the cortical screws, (however some surgeons do this intentionally), with a resultant valgus reduction of the fracture. Questions enquiring whether this was intentional or not were not asked unfortunately.

Debate continues over the impact of the length of incision. The current focus is on minimally invasive techniques and there is a market and patient driver for producing minimally invasive techniques (Ciminiello, Parvizi, Sharkey, Eslampour, & Rothman, 2006; Ogonda et al., 2005) . Part of the original push arises from abdominal surgery, where there is a dramatically improved recovery following laparoscopic surgery over standard laparotomy techniques, though within orthopaedics there are similar benefits in arthroscopic versus open menisectomy. However though intuitively correct there do not appear to be benefits in every surgery, and the impact that making a smaller incision has on correct placement of an implant may obviate any gain (Ogonda et al., 2005). Within this experiment the BTs had a statistically significant smaller incision, however this would not necessarily have provided an overall benefit for the patient as their final screw placement was not as accurate as the ATs.

The simulator allows the user to identify when they have reduced the fracture anatomically as no fracture line is visible in this position. This meant that subjects did not have to make a judgement call on whether they had reduced the fracture satisfactorily. The ability to identify something which is perfectly satisfactory but not perfectly anatomical is acquired through experience. This is reflected in that the median score for reduction by the ATs was lowest, followed by the BTs and the MS scored highest. Moreover the majority of fractures were reduced adequately according to Garden's description (Garden, 1961). It was felt that for initial testing of the simulator then this simplification would be acceptable. Subjects could therefore expend as much effort as they wished to reduce the fracture anatomically.

Time taken to complete procedures varies, but does not necessarily indicate quality, as some trainees may have more trouble utilising the VR interface. Similarly if timing is used in measuring real world performance, a problem with providing instruments may reflect a systems problem, rather than a problem with the operating surgeon.

5.4.6 Confounding Variables

One of the confounding variables within this study is the small number of available subjects at our single institution. Methods of increasing this number involve either travelling to other hospitals, though there are only usually only around two advanced trainees in each centre, or performing the study at longer time intervals, though the trainees generally change centres on a yearly basis. The small numbers may have impacted on the study, and possibly the discrimination ability of the Bon*e*doc simulator will be borne out when larger cohorts are used.

Another confounding variable is the assumption that experience has a more profound effect than innate skill on performance. Thus a naturally gifted BT may perform better than a mediocre subject from the AT group. However there is no definitive method for ascertaining this innate ability, and in the future the Bon*e*doc simulator may be able to be used for testing visuo-spatial ability. In addition within the BTs group there was a range of operative experience. Within both the BT and AT groups there was some variability in operative experience. Although all had less than 3 years experience, some of the trainees were currently fixing as many hip fractures as the advanced trainees. This may have accounted for the inability to find significance between the AT and BT groups on most variables.

5.5 Summary

This study has shown construct validity in that the Bon*e*doc simulator is capable of discriminating between novice subjects and surgical trainees. However it is less capable at discriminating between basic and advanced trainees. One reason may be the similar skill levels between basic and advanced trainees in this operation. From this study, penetration of the hip joint by the lag screw was the most important clinical outcome, and was correlated with level of operative experience. The advanced trainees scored best on screw placement (although not significantly). The increased computer prowess of the medical students did not confer enough benefit to this group to counteract the increased benefit from real world operative experience. Further work is required to develop the complexity of the simulated experience to make obtaining the reduction and the quality of the fracture reduction more challenging.

Performance on the simulator does not necessarily equate to real world performance. Measuring the ability of the simulator to improve real world performance (transfer validity) has not been undertaken. A logical method of addressing this would be a case-control type of experiment. Complicating factors in such an experiment include patient variables such as type of fracture, bleeding propensity and bone density, in addition there are trainee variables such as ensuing that all trainees had the same operative experience. Finally defining objective scores for the real world performance is problematic, unless CT scans are used to identify the exact 3 dimensional location of the screw. The protocol for this type of experiment is discussed further in Section 7.4.

This chapter has described the use of the Bon*e*doc simulator for practicing a procedure which is one of the first operations basic trainees will perform without direct supervision. As such the simulator is capable of allowing them to practice this procedure without exposing the patient to risk, which scored 7.7/10 in importance by earlier qualifying surgeons as discussed in Chapter 3. For the most part DHS fixation of fractured neck of femurs is not seen as challenging to advanced trainees. For this reason, the procedure of pinning a slipped capital femoral epiphysis was selected for testing the ability of the simulator to provide feedback about operative performance in this more advanced trainee group. This experiment will be discussed in the next chapter.

C h a p t e r 6

6 SLIPPED CAPITAL FEMORAL EPIPHYSIS

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

6.1 Introduction

Simulation has a role to play at each stage of training, and probably throughout a surgeon's career. The operation of internally fixing femoral neck fractures is a common procedure used by basic trainees to develop and practice skill in interpreting trajectories from x-ray images. Advanced trainees will have fixed a large number of these femoral neck fractures, and consequently would be less likely to use a simulator for this procedure, unless they had not performed the operation for a considerable period of time. By contrast, very few basic trainees will perform percutaneous cannulated screw fixation of Slipped Capital Femoral Epiphysis (SCFE). SCFE is a disorder where a mechanical slip of the normally stable proximal growth plate (or physis) of the femur occurs. This operation is most commonly performed by either advanced trainees or consultant surgeons. Although there are many similarities with internal fixation of femoral neck fractures, differences such as the abnormal anatomy and youth of the patient demand special care.

This chapter describes the clinical condition of slipped capital femoral epiphysis and the potential complications arising from inadequate treatment. It details how the geometry of this condition was modelled and how a new module of the Bon*e*doc simulator was developed. The chapter continues with a description of the testing of the module on the advanced trainees, and discusses the results from this experiment.

Having a module which was more appropriately challenging for advanced trainees enabled examination of the simulators ability to discriminate between trainees from different years on the training scheme. Additional use of the simulator allowed insight into patterns of operating by trainees. In addition this module was used to test the feasibility of using the simulator to provide an assessment of trainee's performance within a 30 minute time-slot at one of the compulsory education weekends for New Zealand orthopaedic trainees.

6.2 Background

Slipped Capital Femoral Epiphysis affects adolescent boys more commonly than girls, and has an incidence of between 2 and 10 per 100,000 (Lehmann, Arons, Loder, & Vitale, 2006) Left untreated the resultant deformity has significant consequences such as degenerative hip disease, gait abnormalities, and avascular necrosis.

The aetiology of the condition remains unknown, however there are associations with obesity, endocrine disorders such as hypothyroidism and treatment with growth hormone, and abnormal anatomy such as retroversion of the femoral neck and reduced neck-shaft angle.

The pathological features appear to be thin collagen fibrils within the extracellular matrix of the proximal femoral growth plate with presumed weakness in the integrity of the growth plate. In addition Ippolito (Ippolito, Bellocci, Farsetti, Tudisco, & Perugia, 1989) found absent or decreased mineralization of the cartilage matrix of the degenerating zone. Radiographically this decreased mineralization appears as widening of the physis. There are increases in the proteoglycan and glycoprotein concentrations within the proliferative zone of the growth plate. Howorth (Howorth, 1949) describes synovial changes of oedema consistent with those seen on MRI.

1A–E

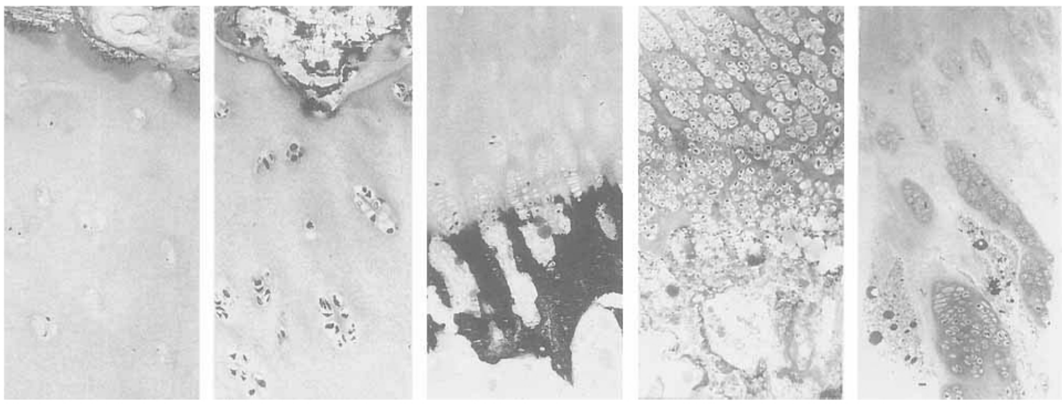

FIG. 1. Proximal femoral growth plate of **(A)** and **(C)** 13-year-old boy, normal; **(B)** 12-year-old girl with preslipping of the proximal femoral epiphysis; **(D)** and **(E)** 13- and 14-year-old boys with mild slipping. In the normal plate, the chondrocytes **(A)** of the resting zone are grouped in small nests containing two to three cells, while in the proliferating and hypertrophic zones **(C)**, chondrocytes are arranged in short columns separated by thick longitudinal septae that are heavily mineralized in the degenerating zone. In SCFE plates, the chondrocytes of the resting zone are grouped in small clusters containing several cells **(B)**, while in the proliferating and hypertrophic zone, chondrocytes are arranged in big clusters separated by thin metachromatic septae **(D)** or by large areas of extracellular matrix weakly or not at all metachromatic **(E)**. Mineralization is scanty in the degenerating zone **(D)**. (Toluidine blue; **A, B:** ×329; **C, D:** ×126.)

FIGURE 6.1: Light Microscopy of slipped capital femoral epiphysis. From (Ippolito et al., 1989).

The loss of integrity of the growth plate means that forces transmitted across the growth plate include shearing strain at this interface, resulting in slippage at this surface. The direction of this slip is classically described as the head moving medially and posteriorly in relation to the femoral neck.

Although this description is accurate, as it describes a relative motion between two parts of the femur, it is somewhat misleading. Rather the epiphysis (femoral head) is held within the acetabulum of the pelvis, and the femoral metaphysis (neck and shaft) slips anteriorly and proximally. These movements are most likely due to muscular forces (from the iliopsoas tendon) and the transmission of force while walking.

6.2.1 Classification and Progression

A number of classifications of SCFE have been produced and are used clinically. These are based on either the chronology, or the mechanical status, or the roentographic appearance of the SCFE.

The chronological classification defines three separate stages, firstly "pre-slip" during which no movement occurs at the physis, though there is widening of the physis visible on x-ray. The "acute slip" stage is defined as lying within 3 weeks of the onset of symptoms. A "chronic slip" is defined as that of slippage over an extended period of time. An "acute on chronic" slip is described as an acute exacerbation on a longer background of symptoms. Many patients with a chronic slip report intermittent pain, and this is thought to be ongoing microslippages. Acute slips have been further defined as those slips without roentographic evidence of healing.

The mechanical classification of weight bearing was first proposed by Loder et al in 1993 (Loder, Richards, Shapiro, Reznick, & Aronson, 1993). An unstable hip is classified as one in which the patient is unable to weight bear even with crutches.

The roentographic classification of SCFE was described by Southwick in his 1967 paper (Southwick, 1967). The difference in the physis line/femoral shaft angles between the normal and slipped side is measured. This is based on two lines being drawn. Firstly a line drawn orthogonal to the plane of the physis as seen on the x-ray and secondly a line drawn running down the femoral shaft (FIGURE 6.2).

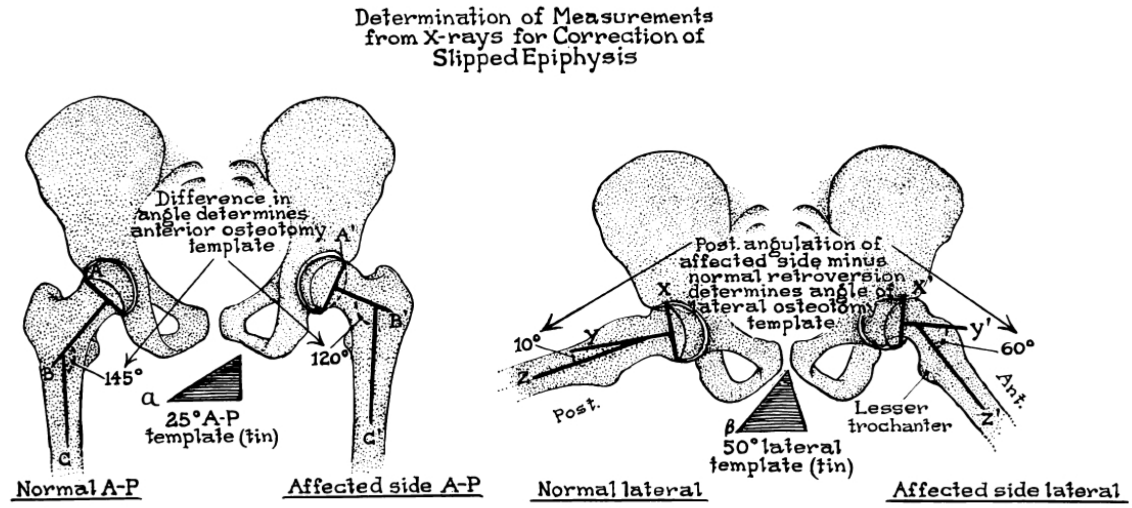

FIGURE 6.2: Illustration from Southwick (Southwick, 1967) demonstrating measurement of the head-shaft angles on (a) AP views and (b) Lauenstein's frog lateral views.

The slip is graded according to the angulation in the AP plane of the head-shaft angle, measured as the difference between the normal and affected sides.

- Grade 1 is Less than 30 degrees of angulation in the AP plane.
- Grade 2 is between 30 and 60 degrees of angulation (70 degrees in original paper)
- Grade 3 is greater than 60 degrees of angulation. (70 degrees in original paper)

6.2.2 Imaging Modalities

6.2.2.1 X-ray

Plain X-rays are usually used to make the diagnosis and grade the severity of the slip. An X-ray taken in the antero-posterior direction (AP) characteristically shows the epiphysis slipping posteriorly and inferiorly. However an early or mild slip may only be appreciated on a lateral or more specifically a frog-leg lateral x-ray. The frog-leg lateral is an x-ray taken with the affected limb flexed at the hip and knee such that the foot rests near the knee of the opposite limb. The hip is then abducted to 40 degrees (Gronefeld & Cornuelle, 1998).

There are two radiographic signs which aid in the diagnosis and are seen on an AP pelvis radiograph, these being Steel's sign and Klein's line. Steels sign shows a blanch in the metaphyseal region; this appearance is created by the medial metaphysis overlying the posterior aspect of the epiphysis (Steel, 1986). Klein's line is a line drawn along the antero-superior aspect of the femoral neck (KLEIN, JOPLIN, REIDY, & HANELIN, 1952)(FIGURE 6.3). On a normal x-ray this line should intersect with the epiphysis, whereas in a child with a SCFE the edge of the epiphysis will either be in line with, or will lie postero-inferior to Klein's line.

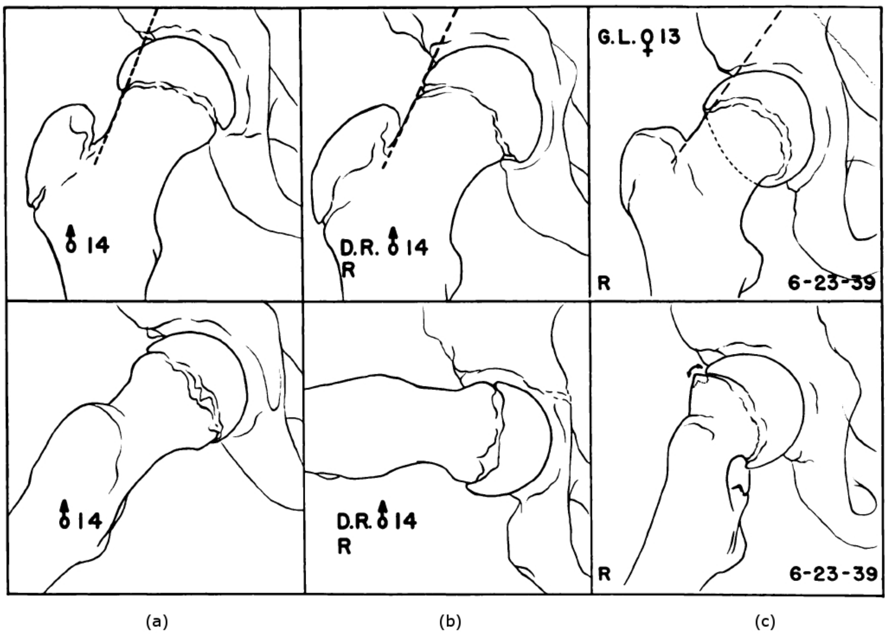

FIGURE 6.3: Illustration from article by Klein et al (KLEIN et al., 1952) demonstrating line along superior margin of neck to ascertain medial slip of epiphysis (a) normal, (b) medial slip, (c) posterior slip..

6.2.2.2 CT Scan

CT Scans are less commonly used due to the risk of radiation. They may be of use in determining the exact position of a screw, the extent of closure of the physis, and for pre-operative planning for osteotomies.

6.2.2.3 Ultrasound

Kallio et al (Kallio, Paterson, Foster, & Lequesne, 1993) showed that ultrasound could be used to identify whether a slip was acute or chronic, on the basis of an effusion being present in the former and remodelling being identified in the latter. This obviates the need to rely on a patient to recall the sometime ambiguous symptoms of hip pains, thus is useful in staging a patient, but currently would not supplant the need for plain x-rays.

6.2.2.4 MRI

Staatz et al (Staatz et al., 2007) found MRI to allow accurate evaluation of the vascularity of the femoral head. Findings showed bone marrow oedema within the epiphysis and metaphysis, as well as morphological deformity and joint effusion.

Two case reports by Lalaji et al (Lalaji et al., 2002) show findings of bone marrow oedema, and globular widening of the physis, with patients during the pre-slip stage.

6.2.3 Complications

The main complications of SCFE are chondrolysis, Avascular Necrosis (AVN) and further slippage, all of which may occur in patients without treatment. However there is significant evidence to show that treatment may also predispose patients to developing the first two of these conditions.

Chondrolysis describes the appearance (usually on x-ray) which results from degradation of the articular cartilage matrix and cells (chondrons), and is defined as being present when joint narrowing is within half of the contralateral side or 3mm in bilateral cases (Aronsson, Loder, Breur, & Weinstein, 2006).. The incidence lies between 2 and 55% with an overall incidence of around 7% (Lubicky, 1996) of all patients with SCFE. It is thought to occur as a result of an autoimmune phenomenon, however there is a large association between chondrolysis and pin penetration. Most studies have only looked at the result of the final screw penetrating the joint. A proposed technique for establishing whether a pin has penetrated the joint is an attempted arthrogram, by which contrast is injected through the wire-cavity. This has not been widely adopted for fear of introducing more particles into the joint, enhancing the immune phenomenon and thereby increasing chondrolysis. A paper presented by Walters and Simon (Walters & Simon, 1980) describes the so-called blind-spot, whereby a wire or screw may lie within the joint, but appear as extra-articular due to the fan nature of the beam and the round femoral head. The extent to which the hip joint is penetrated by a guide-wire (which is subsequently withdrawn) has not been reported. This reporting relies on an admission of error on the behalf of the operating surgeon, and may have medico-legal ramifications.

Avascular necrosis describes the death of bone cells due to insufficient blood supply. The appearance on x-ray may be unremarkable at first. Subsequently the bone develops a mottled appearance. This appearance is due to resorption of bone by osteoclasts and new bone formation in areas which are revascularised. Further progression involves cyst formation, sclerosis and collapse of the head.

The interruption to the blood supply may be due to either compromise of the vessels feeding the epiphysis, namely the artery of the ligamentum teres, and the epiphyseal branches of the medial and lateral circumflex femoral arteries. This interruption may occur as a result of either disruption to a vessel (due to the slippage or reduction thereof) torsion or disruption by a screw or guide-wire. A landmark paper by Brodetti in 1960 (Brodetti, 1960) describes this blood supply in the juvenile and adolescent age group. Avascular necrosis may occur within the entire epiphysis or more locally. More localised regions of avascular necrosis are thought to occur as a result of a screw lying immediately subchondrally (Riley, Weiner, Gillespie, & Weiner, 1990).

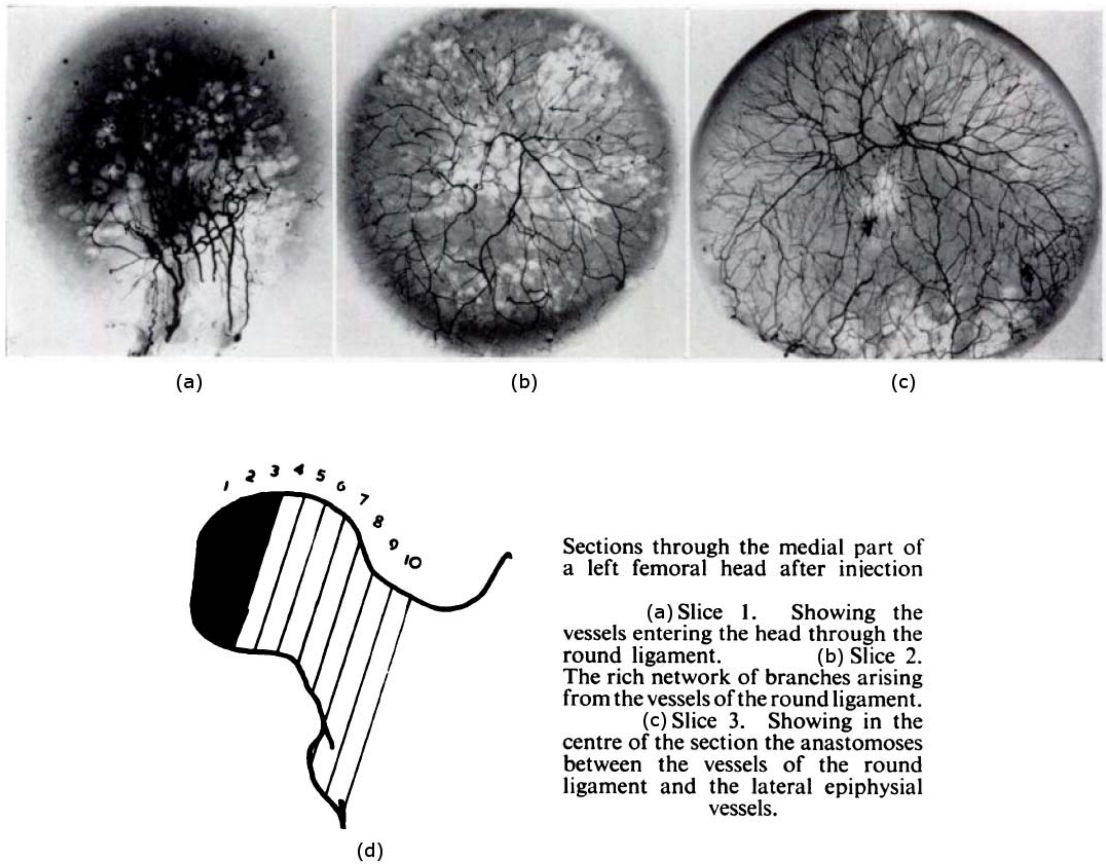

FIGURE 6.4: Figure adapted from Brodetti (Brodetti, 1960), showing how the anastomosis between vessels of the round ligament and the lateral epiphyseal vessels lies in the supero posterior region of the epiphysis.

Further slippage of the epiphysis may occur if the physeal plate remains unstable and the condition untreated. With those SCFE treated by screw fixation, the length of the screw is important. A paper by Carney et al (Carney, Birnbaum, & Minter, 2003) suggests that if less than 5 screw threads (on either side) do not pass into the epiphysis, there is the potential for the epiphysis to continue slipping. The risk of the contralateral side developing a SCFE is as much as 31% (Bidwell & Susan

Stott, 2006), leading to discussion as to whether the contralateral side should be prophylactically treated, or simply monitored more closely.

6.2.4 Treatment

Surgical treatment of SCFE is based on two main decisions. Firstly should the slip be reduced or pinned in situ, and secondly which method of pinning should be used. Currently the most accepted viewpoint is that SCFEs should not be reduced and instead the deformity accepted, with the understanding that some remodelling will occur. This is because reducing the epiphysis has been associated with an increase in avascular necrosis (Tokmakova, Stanton, & Mason, 2003) and should this remodelling not be adequate there is still the possibility of performing corrective osteotomies.

The most common method of treatment currently is the percutaneous placement of a single cannulated screw (Aronsson et al., 2006). This technique was first described by Morrissy (Morrissy, 1990). The use of multiple cannulated screws has been associated with increased chances of screw penetration into the joint and resultant chondrolysis.

Key stages of the procedure are,

1. Estimation of the correct entry point by using a guide-wire. This is performed by placing a guide-wire on the skin, taking an x-ray using the image intensifier in both AP and lateral planes and marking the skin accordingly.

2. Making a stab incision, and then advancing the guide-wire under image intensifier guidance.

3. The guide-wire should be angled orthogonal to the physis, this angle alters the correct entry point of the wire into the bone (described in next step).

4. The correct entry point lies on the anterior cortex of the femoral neck, rather than the more lateral position through which a femoral neck fracture is fixed. The severity of the SCFE will affect this placement, as the entry point advances proximally up the neck with increasing severity of slip.

5. The wire is advanced into the epiphysis until it is around 5mm short of the articular surface.

6. A depth-gauge is then used to identify the correct length of screw.

7. The definitive screw is then placed over this guide-wire and advanced until at least 5 screw-threads of one side of the screw are seen to lie within the epiphysis.

8. The guide-wire is then withdrawn and the skin closed.

As noted above it is absolutely imperative that the final cannulated screw has not penetrated the hip joint, as this would inevitably lead to chondrolysis and erosion of the articular cartilage. Methods of ensuring this does not happen include the approach-withdraw method of Moseley (Moseley, 1985). In this method the hip is screened by x-ray while internally and externally rotating the hip. This should identify whether or not a screw has penetrated the hip joint, but is not completely fool-proof.

6.3 Methods

This section describes how the SCFE module of the simulator was developed, and then used to test a number of hypotheses. These hypotheses included; the feasibility of using a virtual reality simulator within the constraints of a training weekend, whether there was a difference in the accuracy with which trainees from different years operated, and finally whether there were different patterns of operating amongst advanced orthopaedic trainees.

6.3.1 Development of model

The SCFE module contains a virtual model of a slipped capital femoral epiphysis, based on CT scan data from a patient with a chronic slip. Ethical approval for collection and use of the CT scan data was given by the Northern Regional Ethics Committee. DICOM images were imported into 3DView (www2.cmp.uea.ac.uk/~rjal/3DView.htm), volume rendering software which is freeware. Within this package Hounsfield values from the CT scan were used to create an isosurface (a 3 dimensional contour of similar values) which represented the external bony surfaces (FIGURE 6.5). This isosurface was loaded as a mesh into the freeware CAD package Blender (www.blender.org). The generic proximal femur from the femoral fracture module was imported into Blender and translated, scaled and deformed until it overlay the patient's normal side (FIGURE 6.6). Using the knife tool, the generic proximal femur was divided into an epiphysis and a metaphysis along the physeal plate. The cut femur was then mirrored onto the affected side, and the metaphysis realigned. The epiphysis was then rotated and translated to align with the slipped epiphysis (FIGURE 6.7).

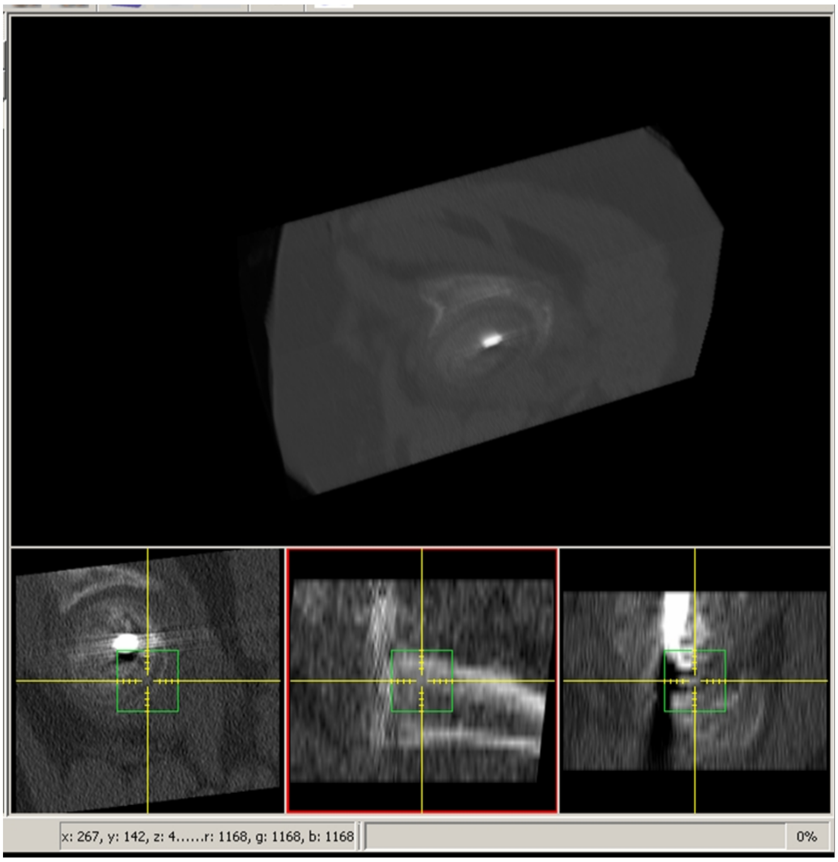

FIGURE 6.5: Screenshot from 3DView showing identification of cortical bone for automatic segmentation and isosurface generation.

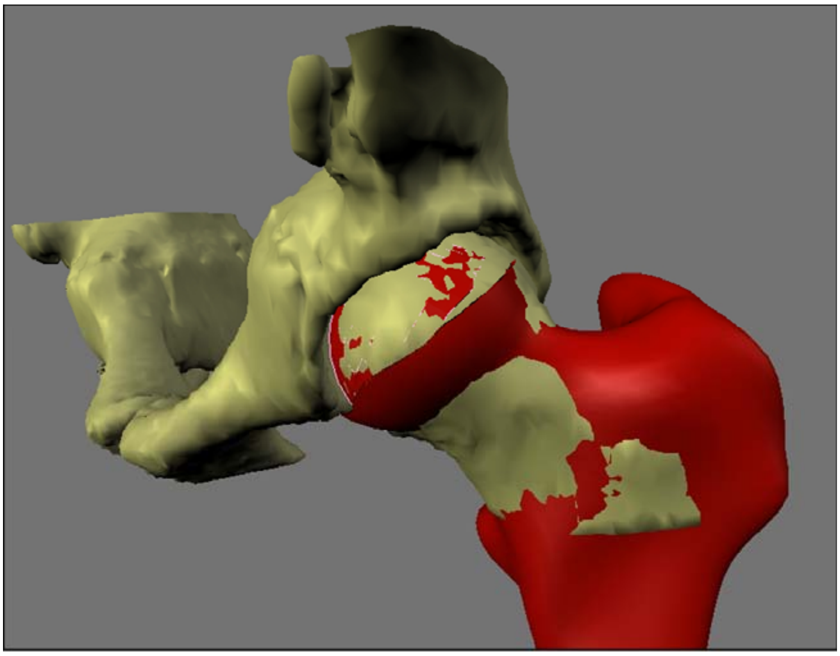

FIGURE 6.6: The generic femur was translated, scaled and deformed within Blender to overlay on the patient specific mesh.

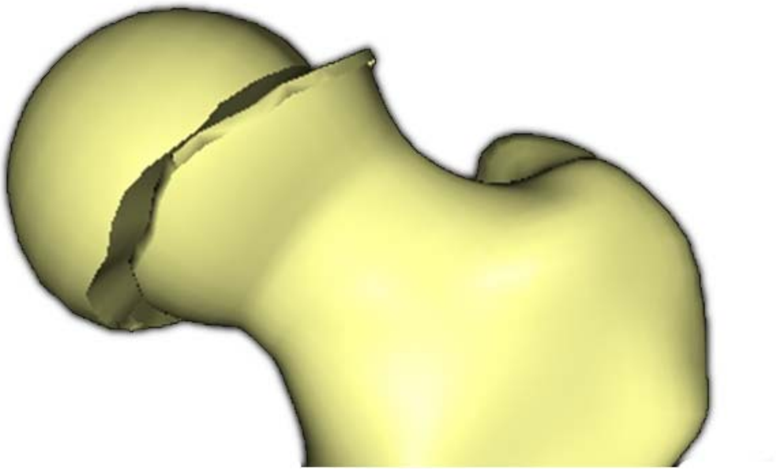

FIGURE 6.7: The virtual SCFE with some bony remodelling.

This slippage was produced by rotating the epiphysis by 9 degrees posteriorly with respect to the femoral shaft, 16 degrees of varus angulation and 14 degrees of internal rotation, and finally translated, which apart from the posterior angulation, is similar to those models presented by Kordelle (Kordelle, Millis, Jolesz, Kikinis, & Richolt, 2001) and Rab (Rab, 1999). Once the epiphysis and metaphysis had been aligned to their slipped positions, the bone around the physeal plate was smoothed and re-aligned to mimic the appearance of bony remodelling which occurs in an acute on chronic slip (FIGURE 6.7). The new virtual femur bone with the SCFE was then imported into the simulator.

The shape of the physeal plate is of interest as it is not a simple flat plane but rather is scalloped and convex (FIGURE 6.8). The terminology of calling the condition a slippage along the physis may in fact belie the occurrence of a certain amount of angulation, and perhaps even torsion, during the pathological displacement. This morphology has been investigated on a number of occasions, but is not generally considered in the most descriptions of the disorder. A study by Tayton et al (Tayton, 2007) on 11 juvenile femurs demonstrates the presence of an epiphyseal tubercle, and describes difficulty in allowing slippage without rotation. The growth plate of the virtual SCFE was modelled accordingly with slight scalloping and convexity.

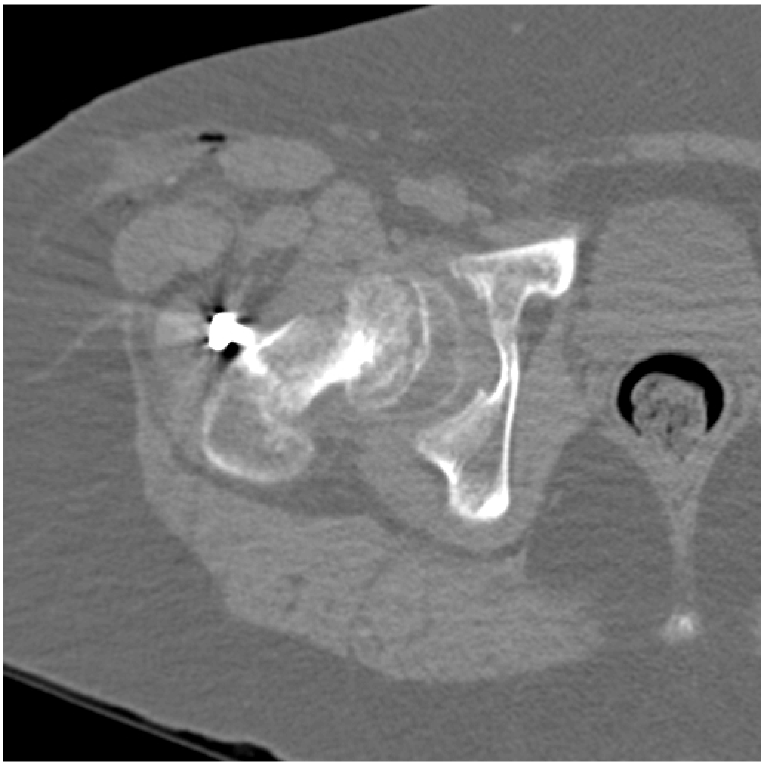

FIGURE 6.8: Axial CT through physis demonstrating convexity and scalloping.

According to the literature (Aronsson et al., 2006) the best position of a single cannulated screw is with its tip at the apex of the epiphysis, and aligned with a point at the centre of the mid-point of the physeal plate. Because the femur was modelled with sector elements radiating from the apex, the ideal spot could be easily identified. The trajectory was then identified by aligning axes from the apex of the epiphysis to the midpoint of the physeal plate. Extrapolation of this trajectory confirmed the target entry point to be on the anterior cortex of the femoral epiphysis(FIGURE 6.9), which is in keeping to the literature (Aronson & Carlson, 1992). The line of this trajectory was defined as the short/long axis. The anterior and superior axes were selected similarly to the femurs used for femoral neck fracture on the basis that the supero-inferior plane can be calculated from the distal femoral condyles, and the anterior plane lies orthogonal to these points, as can be seen on FIGURE 4.31 (Wu et al., 2002).

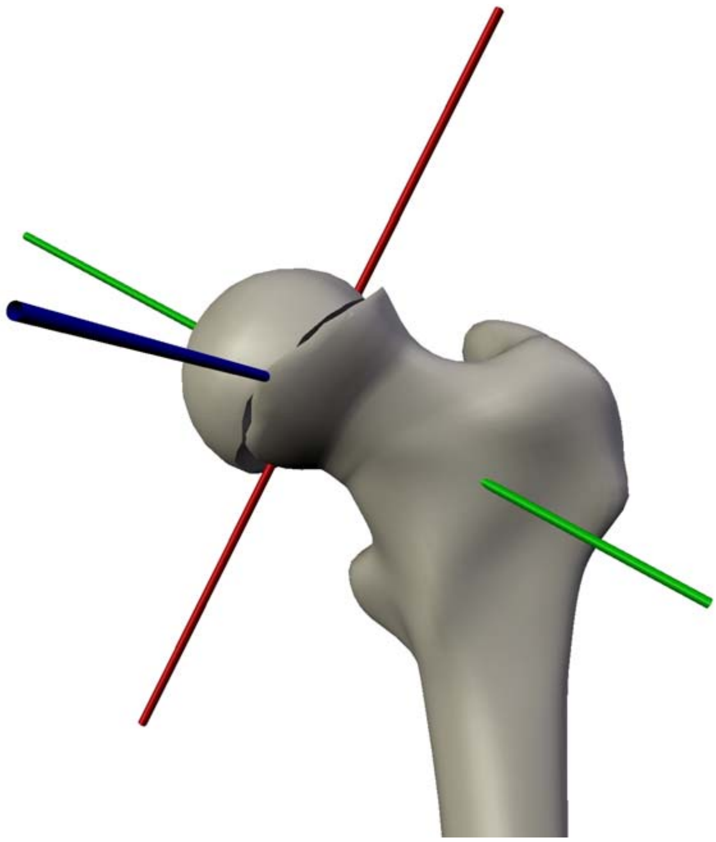

FIGURE 6.9: Axes of epiphysis, showing how entry point should be on the anterior aspect of the femoral metaphysis.

A critical factor is placing the screw orthogonal to the plane of the physeal plate(Aronson & Carlson, 1992). The deviation of the trajectory from this plane was calculated using the Pythagorean Theorem as described in Appendix F. Calculating this angle in real time, means the simulator is able to tell whether the entry point is positioned too inferior or posterior, as it is possible to triangulate to the ideal point and report the deviation. This ability means that the simulator could be used in a training mode, rather than assessment mode. For the purposes of this experiment the training mode was switched off.

Caution must be exercised before allowing trainees to use a teaching mode, as continuous feedback may negatively impact on training (Schmidt & Wulf, 1997). A study by Wierink (Wierinck, Puttemans, Swinnen, & van Steenberghe, 2005) showed that dental students who had received augmented visual feedback performed less well in retention tests than their counterparts who had not received the extra feedback. This is because there is a tendency for early trainees to rely on this opinion rather than working out whether and why their entry point is not positioned appropriately for themselves. This is analogous to what happens in the real world when a trainee is being supervised. It is very hard for the supervisor not to tell the trainee where they are going wrong, and equally it is very hard for the trainee to not rely completely on the supervisor once the supervisor starts advising corrections. This is partly because the trainee does not want to harm the patient, and partially because there is a hierarchy of authority which the trainee will not usually challenge.

To avoid complexity in the operation it was elected to model a grade 2 acute on chronic slip, such that trainees did not have to decide on controversial aspects such as reduction of the slip. In addition it was elected to only allow trainees to pass a single screw.

The steps of the procedure which are simulated include identification of the entry point, ascertaining angulation and depth of a guide-wire, using a depth gauge to select correct screw length and finally positioning the cannulated screw, as summarised by Aronson (Aronson & Carlson, 1992).

The position and pose of the virtual image intensifier can be altered at any stage, and images taken to guide the placement of the guide-wire. The skin can be marked to assess the correct entry point. The entry point and angulation can be adjusted and readjusted infinitely. Once the guide-wire position is deemed acceptable, the depth gauge is used to select a screw, which is then inserted with image guidance to ascertain the final position of the screw relative to the physis and articular surface.

6.3.2 Subjects:

All 46 advanced orthopaedic trainees attending the biannual training weekend completed the simulation exercise as one of the sessions. The training weekends are a compulsory component of the advanced training. This was the first virtual reality exercise for most but not all of the trainees, as 6 of the trainees had been involved in a construct validity experiment described in Chapter 5.

6.3.3 Protocol:

The simulator was demonstrated to the trainees in a combined 10 minute briefing session by inserting a distal locking screw into an intra-medullary femoral nail. Use of this procedure ensured that the trainees did not have time to review or discuss aspects of the SCFE operative procedure with their colleagues prior to commencement of the assessment. Following this demonstration, trainees carried out the 'virtual SCFE pinning' within separate 30 minute sessions for each of the four groups of residents (1st year through to 4th year). A computer lab with 13 identical computers was utilised. Help was on hand to answer individual questions with regards to the interface as they arose.

6.3.4 Data acquisition:

Similar to the DHS module, the trainees self-assessed their performance at the conclusion of the procedure, were then given the objective score-sheet and were able view the SCFE with the bone translucent and visualise the position of the screw from any direction.

In addition the simulator acquires numerical data concerning their individual performance including:-

- Screw placement error in 3 planes
- Angulation of the screw from the plane of the physis
- Number of screw-threads within the epiphysis
- Number and location of misplaced drill-holes.
- Amount of x-rays taken,
- Number of times the image intensifier was shifted from AP to lateral.
- Surgical time

The simulator identifies the final position of the screw tip, and records its position relative to the ideal spot. This ideal spot is defined as a point 5mm short of the articular surface along a line passing through the centre of the epiphysis and orthogonal to the physis, which allows a minimum of five threads to be across the physis, as described by Morrissy (Morrissy, 1990). From this position, measurements are given in the antero/posterior, supero/inferior and short/long axes, as well as the absolute distance from the ideal spot to the tip of the placed screw. The method used to calculate these results has been described in Chapter 4.

In addition, the location of the tip of each misplaced drill-hole is recorded, such that a graph of the 2 dimensional location in antero/posterior and supero/inferior planes can be drawn (FIGURE 6.10).

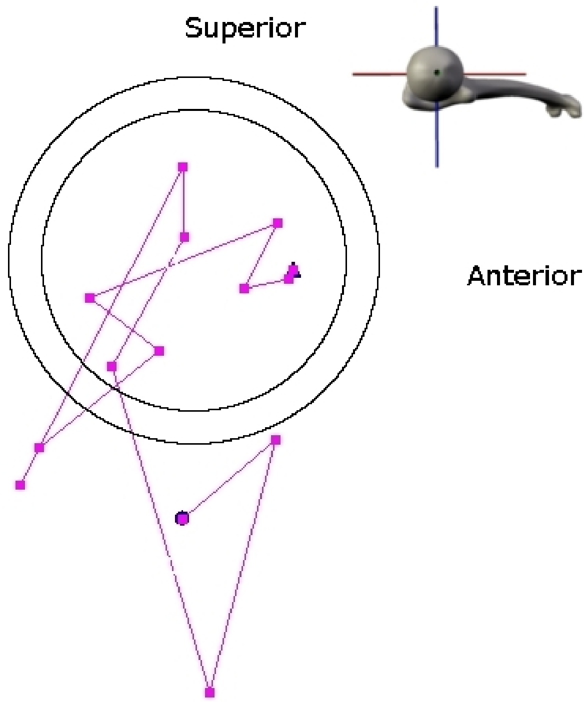

FIGURE 6.10: Graph showing wire-tips from mistakenly drilled holes, from initial wire (depicted by a circle) to final screw (depicted by a triangle).

This graph gives an indication of the manner in which a trainee operates. From this graph the distance of this "error-path" can be calculated (Appendix G), which allows comparison between multiple trainees.

6.3.5 Data analysis:

The objective scores from the simulator were imported into Statistical Analysis System (SAS 9.1) software (SAS Institute, Cary, North Carolina, U.S.A.). The non-parametric Spearman's correlation co-efficient was used to determine the correlation between parameters from the virtual surgery. Differences between year-groups were tested for significance using non-parametric Kruskall-Wallis ANOVA.

6.4 Results

6.4.1 Demographics and Experience:

All 46 orthopaedic surgical trainees in New Zealand participated in the testing sessions. Five of the procedures had to be subsequently excluded from analysis as five of the trainees mistakenly requested a screw length of less than 0mm, causing the software to crash. Consequently, the simulated operations were performed by 10 first year trainees, 10 second year trainees, 11 third year trainees, and 10 fourth year trainees.

6.4.2 Scores on the Simulator:

6.4.2.1 Guide-wire Penetrations of the Hip Joint

Each time a trainee decided their guide-wire was incorrectly placed and withdrew it, the simulator recorded the position of this guide-wire. Eighteen of the trainees breached the hip joint with the guide-wire (5, 4, 7, 2 respectively in each of the year groups), amounting to a total of 31 penetrations. FIGURE 6.11 shows the mistakenly placed guide-wires for all 1st and 2nd year orthopaedic surgical trainees. The median (and range) number of times the entry point of the guide-wire was changed was 3 (0 to 24), and the number of times the guide-wire angle was changed was 4 (0 to 17) for all trainees.

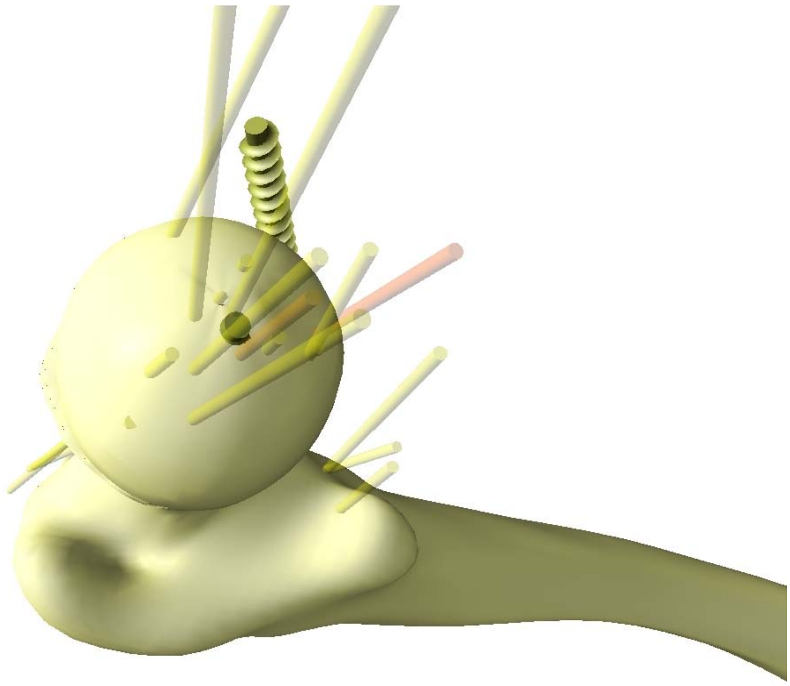

FIGURE 6.11: Penetration of the hip joint by 1st and 2nd year trainees.

6.4.2.2 Screw Position within the Epiphysis

There was no statistical difference in the accuracy with which screws were placed between trainees from each of the 4 years, or between earlier trainees (years 1 and 2) and later trainees (years 3 and 4). Twenty seven of the 41 trainees placed the screw in the postero-superior quadrant of the epiphysis (FIGURE 6.12).

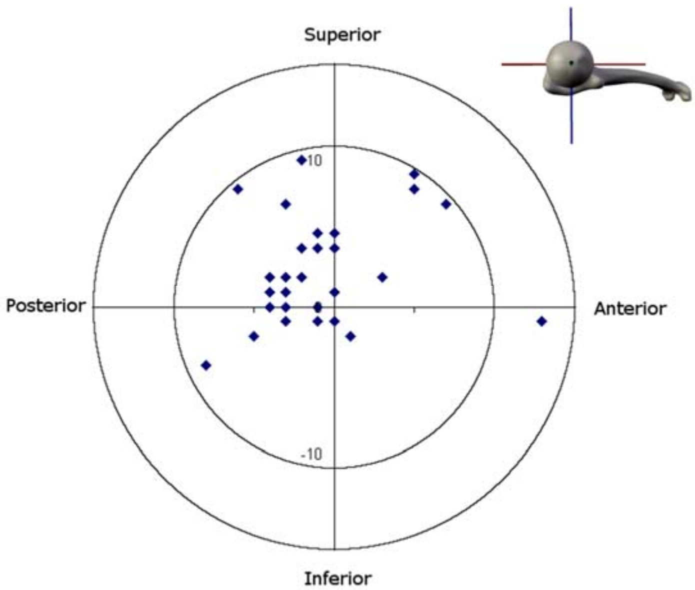

FIGURE 6.12: Screw tip placements measured in mm relative to the ideal spot for all trainees (insert shows plane of graph).

In the antero-posterior plane, the trainees placed the screw with a median (and range) distance of -1.5mm (-6 to 7mm), with positive numbers reflecting an anterior placement and negative numbers reflecting a posterior placement. In the supero-inferior plane the trainees placed the screw with a median of 2mm (-2 to 10mm) in the superior direction, with negative numbers reflecting an inferior placement and positive numbers reflecting a superior placement.

With regards to screw length, two screws breached the articular surface of the femoral head. These two screws were placed by one 1st year trainee and one 2nd year trainee respectively. The number of threads within the epiphysis had a median (and range) of eight threads (three to 11 threads). Three screws were placed with less than five threads across the physis, four screws were placed with five threads across the physis and 24 screws were placed with six or more threads across the physis. The three screws with less than five threads across the physis were placed by a first, second and fourth year trainee.

A regression analysis was used to look at factors predictive of a satisfactory screw placement. The final screw placement was defined as satisfactory if 5 or more threads across physis (Carney et al., 2003); no closer than 5 mm to the articular surface (Morrissy, 1990) and no more than 10mm from ideal in either AP or superior/inferior planes (Aronson & Carlson, 1992). Based on this, 15 screws were satisfactory and 16 unsatisfactory. The factors considered in the regression analysis were the seniority of the trainee, number of guide-wire changes, number of X-rays taken and number of II moves.

6.4.2.3 Obliquity of Screw to Physis

The angle with which the screw intercepts the physis is measured in both anterior/posterior and superior/inferior planes. There was no statistical difference between the year groups or between the early and late trainees. The median (and range) angle in the anterior direction was 0.85 degrees (-29.1 to 25.2 degrees), with positive numbers reflecting an anteriorly directed screw. The median (and range) angle in the superior direction was 0.5 degrees (-17.7 to 29.3 degrees), with positive numbers reflecting a superiorly directed screw.

With regard to the positioning of the screw, variation in the placement of the screw-tip in the anterior plane was correlated with the anterior intercept of the physis, indicating that screws tend to lie orthogonal to the growth plate in the antero/posterior plane. Likewise screw-tip positioning in the superior plane was correlated with the superior intercept, indicating that screws tend to lie orthogonal in the supero/inferior plane as well. Regression analysis on intercepts and angles shows absolute screw position predicted by intercept and angles.

6.4.2.4 Number of X-rays taken and Image Intensifier Moves

The median number of times the image intensifier was changed from AP to Lateral position was 14 (4 to 52). The median number of times an X-ray was acquired was 36 (11 to 74) for all trainees. There was no correlation between the number of X-rays and the final screw position (rho=-0.11). There was, however, a positive association between the number of X-rays taken and both the depth of misplaced drill-holes (rho=0.52, $p<0.001$) and the time taken to complete the procedure (rho=0.60 $p<0.0001$).

6.4.2.5 Time to complete surgery:

The median time to complete the surgery was 11:33 minutes with a range of (3:08 to 25:04). Previous experience on the simulator did not affect the accuracy or speed of surgery.

6.4.2.6 Self-Assessment on the Simulator:

Across the group a trainee's assessment of their own performance was not correlated with final screw position, time taken, X-ray dose or screw thread length in the epiphysis.

The most accurately placed screw lay 1mm posteriorly, 0mm superiorly, and 2mm short, it was angled 4.9 degrees anteriorly and 8.9 inferiorly with respect to the physis, required 66 x-ray images and was self assessed as 3/5.

6.4.2.7 Correlations between parameters

The second part of the analysis sought to identify correlations between variables within the trainee population.

Radiation dose was captured as the number of x-rays which were requested. There was no significant correlation between dose and the absolute screw position. There was a significant correlation between dose and time taken ($p<0.001$), with increasing time associated with increased dose, and as expected dose is related to the number of corrections to angle and altered position as well as the depth of misplaced drill-holes(all $p<0.01$).

The correlated factors for final screw position were time taken ($p<0.01$) and intercept of the screw with the centre of the physis ($p<0.01$).

6.4.3 Patterns of Operating

There was a wide variation in the styles of operating, with some trainees taking significantly more x-rays than others (range of 11 to 74 x-rays), some trainees making significantly more adjustments to the guide-wires (range of 0 to 24), and some trainees taking significantly longer to complete the surgery (range of 3 to 25 minutes).

Further analysis of the mistakenly placed guide-wires shows evidence of the variety in how trainees operate. FIGURE 6.13 shows three representative error paths for wire re-positioning from the first attempt at wire placement to the final position of the screw. It can be seen that all three trainees achieved satisfactory end-placement of the screw. However some trainees drift erratically along this course, while others are able to make fewer deviations from their initial misplaced drill-hole to their final screw placement.

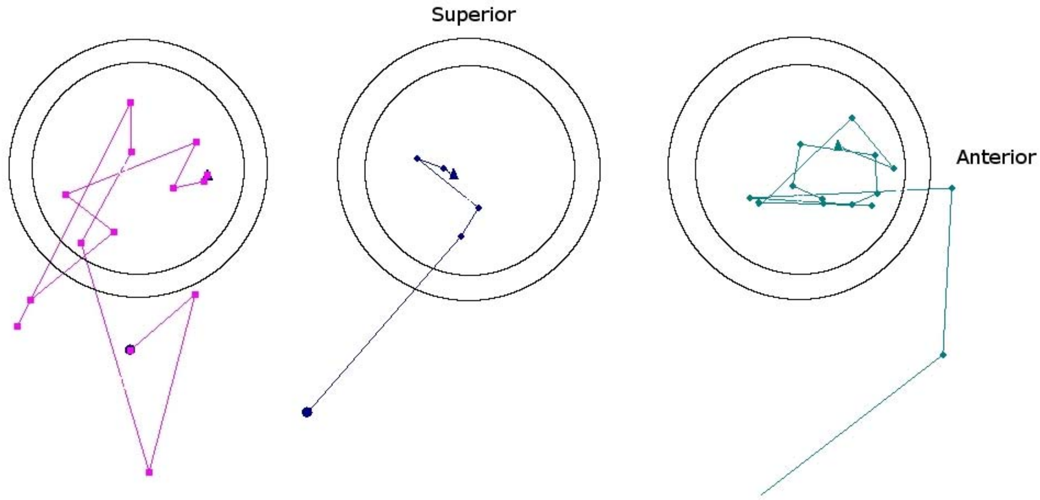

FIGURE 6.13: Error-paths for 3 representative trainees, illustrating the different styles of operating, from initial mistake (circle) to screw placement (triangle).

Comparison between a multitude of trainees is not possible using this "error-path" style of figure, however by calculating the total length of this "error-path" an amalgamation of how far from the path the trainee deviates is calculated. A scatter-plot of this "total error length" compared with the final accuracy of placement of the screw delineates several styles of operating (FIGURE 6.14). The normal group has a relatively low "total error length" score and a small absolute distance from the ideal spot. A second group with high "total error length" and small absolute distance, consists of trainees who are either "gilding the lily" and should refrain from altering the guide-wire as much (as by repeatedly advancing the guide-wire they are compromising the integrity of the bone), or are experiencing some difficulty in obtaining the correct position. Thirdly there is a group of trainees who are operating in a "slap-dash" manner, with a low "total error length" but a high absolute distance, this group has accepted a bad position for their screw, and should actually be re-drilling to improve the position. Finally there is a dangerous group, with both a high "total error length" and large absolute distance from the ideal spot; members of this group must be struggling with the conceptualising the position of the guide-wire with the end result that they have placed the final screw far from acceptable, without asking for help.

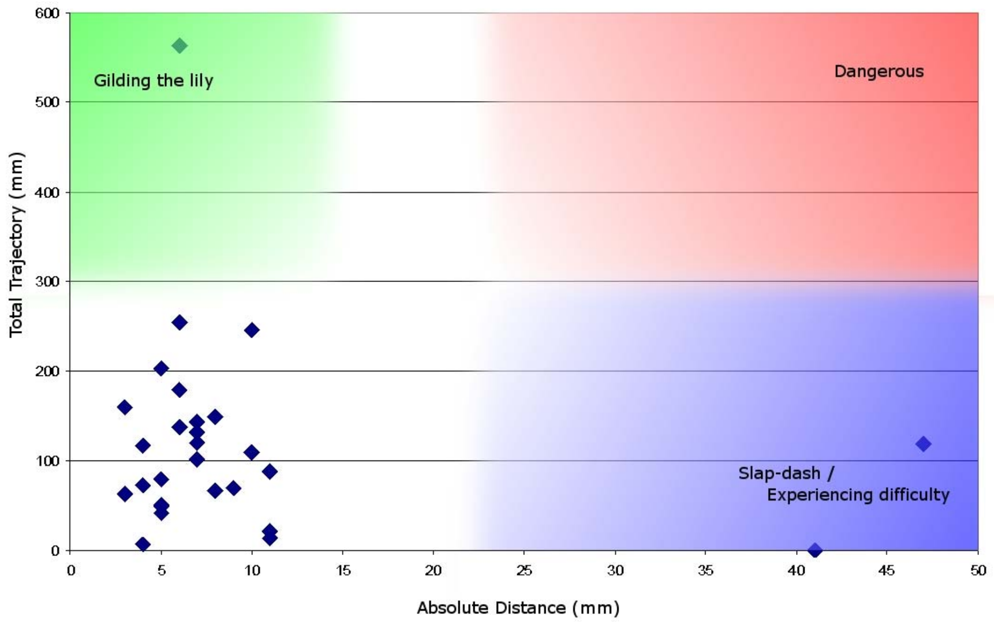

FIGURE 6.14: Scatter-plot of total trajectory versus absolute distance of screw-tip to ideal spot.

6.4.4 Ability of simulator to be used within weekend.

As the simulator was a trial version, it was possible for trainees to request a screw with a negative length, due to a lack of failsafe on the depth gauge. This error meant that no results were possible for 10 operations. However the time allowed for the session of around 30 minutes meant that although this was the first attempt on the simulator by most trainees, all of the trainees were able to perform the surgery within the allotted timeframe. Outside of the problem with the depth-gauge the simulator and the format of using the simulator within the weekend worked well 23 of the trainees signalling that they needed more practice and there was a request by the organising committee to conduct another experiment at a future training weekend. The results for each trainee were available to the committee.

6.5 Discussion

By virtue of having all advanced orthopaedic trainees in New Zealand operating on an identical virtual slipped capital femoral epiphysis, analysis can be conducted into the most common location of the screw as well as the varying styles with which this screw was placed. Twenty seven of the 41 screws were placed in the postero-superior quadrant which is thought be most likely to compromise the blood supply to the head. Although at first appearance displacement of around 5 mm does not seem important, Brodetti et al (Brodetti, 1960) demonstrated that the lateral epiphyseal vessels enter the head in the postero-superior quadrant and anastomose with vessels from the teres ligament very close to the mid-point. As all trainees operated on the same virtual patient it is possible to easily identify patterns common to all trainees. In this way common pitfalls can be easily identified, and described.

6.5.1 Accuracy of Screw Placement

There is an expectation that trainees towards the end of their training would perform the surgery more accurately, and with fewer mistakes. To some extent this was evident in the results as the 4th year (final year) trainees breached the hip joint with the guide-wire fewer times than other groups. The only joint penetrations by the screw occurred with screws inserted by one 1st year and one 2nd year. With regard to accuracy of final screw placement however, there were no significant differences between the different year-groups. A reason for this may be that as more 1st and 2nd year trainees managed to crash the simulator than their 3rd and 4th year counterparts, their scores may have been worse had the simulator not crashed.

The lack of difference in accuracy may be due to several reasons. These reasons include the fact that trainees in New Zealand have a greater experience in treating patients with SCFE owing to the high incidence of SCFE within its population (Stott & Bidwell, 2003). Differing amounts of previous paediatric operative experience amongst the trainees means that some first year trainees will have had as much experience pinning SCFEs as some fourth year trainees. The lack of difference may also be accounted for by the trainees' great wealth of experience with fixing femoral neck fractures. Knowledge of the anterior placed entry point (Aronson & Carlson, 1992) may have been enough to allow them to adequately perform the procedure.

This premise that trainees at the end of their training will perform better than trainees at the start of their training on the simulator is based on several concepts, all of which are moot. These concepts include that here is a difference in how well trainees with different levels of experience perform the task in the real world. This in turn is based on the principle that training will increase the ability of trainees to perform tasks. The numbers of trainees within New Zealand available for this experiment must be enough to show statistical difference. The simulator interface must be simple enough or close enough to the real operating theatre such that difficulties using the simulator do not impact on trainee's performance. Finally the parts of the surgery which distinguish the performance of the final year trainees must be represented in the simulator.

6.5.2 Graduated surgical ability by levels of experience

Common sense dictates that practice makes perfect (Guest et al., 2001; Ross, 2006), and indeed there are numerous articles which testify to the fact that surgical units which specialise in certain procedures have better surgical outcomes (Huckman & Pisano, 2006; Shervin et al., 2007). Most construct validity papers use different levels of experience as a surrogate marker for expertise. However it is principally simulators which are able to provide evidence for this point, due to the ability to standardise the test/virtual surgery which is performed. Most of these papers use experts versus trainees, rather than looking within the trainee pool, and it may be that it is only after many years of experience that a detectable difference is noted. In his article describing how experts become masters (Ross, 2006) details that it takes 10 years of dedicated practice to master a skill. Thus there may not be any discernable difference between years 1 to 4 on the training programme. Added to this is the fact that there will be a variation in the innate ability of the trainees, with a naturally gifted first year trainee possibly outperforming an experienced but innately mediocre fourth year trainee.

6.5.3 Effect of Previous Experience

A potential confounder in this study is the fact that some of the trainees had previous experience with the DHS module of the simulator, however these trainees did not perform significantly differently to the other trainees. As described in Chapter 5, previous analysis of performance with the DHS module showed no significant learning curve with scores from six different operations. This has implications in the design of other experiments, as due to the demand of work-load on trainee's time, it is often difficult for them to commit to experiments which may require some hours to perform.

6.5.4 Methods of assessing skill

Methods of assessing technical skill amongst trainees often rely heavily on preceptor ratings, with problems such as leniency, inconsistency, restriction of range and the halo effect (Iramaneerat & Yudkowsky, 2007; Martin et al., 1997). The Bon*e*doc simulator does not suffer from these errors as there is an objective score for each trainee. The simulator allows testing of trainees without the influence of their supervising surgeon in the room. The results of the virtual surgery are available to the supervising surgeon, this is analogous to the surgeon seeing the final x-ray of the procedure, however the simulator provides an easy method of assessing all the mistakes made along the way. The impact supervising surgeons have on trainees is variable, and Bon*e*doc could be used to identify the extent to which this occurs by allowing repeated performance of a procedure on standardised patients, with the aim of creating more objective scoring.

6.5.5 Modus Operandi

There are different modus operandi by which trainees operate, however there are no papers within the literature examining the effect of these different styles on performance. This exercise produced examples such as some trainees taking 4 times as many x-rays to perform the surgery, some trainees adjusting the guide-wire up to 10x more often, and some taking 6 times longer to perform the surgery. Despite these huge ranges, none of these factors were correlated with the final position of the cannulated screw. A system of assessment which only looks at post-operative x-rays might be overlooking the morbidity associated with multiple passes of a guide-wire. Equally deciding that a trainee will never place the screw accurately, just because he has failed on his first few passes is not necessarily correct either. The Bon*e*doc simulator is able to record these different patterns, and hence allow further analysis. This analysis could either be based on following trainees on multiple examples of the same procedure, or multiple different operations to ascertain whether training has an effect on their style of operating. It is assumed that as trainees advance, they will become more confident in knowing where their drill-tip lies, and hence need to use less x-rays. However this reduction in use of x-rays may only be a reduction relative to their initial behaviour and as a fourth year trainee they may still be taking more x-rays than a particular first year.

The variation in location and number of misplaced drill-holes displays interesting patterns when comparing different trainees. From the initial incorrectly placed guide-wire, the trainee then has to estimate how to correct this deviation and place another guide-wire. By graphing the ‘error path’ it is possible to identify how easily the trainee corrects their position, or whether they overshoot. A line segment connecting each sequential mistake can be drawn from the first mistake through to the final screw placement. The length of this line gives an indication of how much the trainee over-corrects each mistake. As discussed earlier there is no significant difference between trainees from each year group, however the difference between individuals is marked. Anecdotal comparison of these styles with performance within the real operating theatre suggests a correlation, and will form the basis of future work.

6.5.6 Feasibility of Using within Weekend

Within a training weekend, providing enough faculty members to oversee the trainees is logistically demanding. A simulator which runs on standard computers affords the option of assessing trainees. VR simulation in this setting can be done with a large trainee/faculty ratio, and frees up faculty to engage with trainees in "live patient" type scenarios. Although this was essentially a beta-trial, on the basis of the success of this first experiment, further sessions are planned for future training weekends.

6.5.7 Use in Selection

The risk of litigation against selection committees by failed candidates has seen increased dependence on standardised interviews and the removal of job references as criteria which can be used to rank candidates. This is largely as the process must be transparent. These job references were one of the key methods the committee has in identifying the manual and spatial dexterity of candidates. Without job references the selection system is capable of grading candidates' knowledge, communication skills and decision making, but has no means of assessing the dexterity which is a vital part of being a good surgeon. In this arena simulators such as Bon*e*doc may be able to provide some objective scores to re-address this balance.

6.6 Summary

This chapter describes how the Bon*e*doc simulator provides a feasible method of assessing orthopaedic trainees' skill at placing a screw in a 3-Dimensional location using image guidance. This method is suitable for use within a normal training weekend setup, from both logistical and financial viewpoints, as it does not rely on expensive hardware. By testing all trainees on the same virtual bony geometry and with the ability to identify exactly the position of the screw, it is possible to identify and report back trends from the whole group. The majority of screws (27 of a total 41) screws were placed in the postero-superior quadrant, which is thought to place the epiphysis at risk of avascular necrosis.

Earlier trainees made more mistakes than trainees further along their training program with a single 1st and 2nd year trainee penetrating the hip joint with the screw, a recognised complication of the operation in the real world. Trainees from the first three years penetrated the hip joint with a guide-wire, while no final year trainees made this error. No statistical difference was found in the accuracy between year-groups with which screws were placed.

The experiment revealed different patterns of operating with considerable difference between individual trainees with respect to the amount of x-rays used, the number of misplaced guide-wires and the time taken to complete the procedure. However neither of these styles were correlated with improved screw position. This has implications for further studies which may incorrectly focus on for example the use of x-rays as a marker of performance, when for the patient the final position of the screw may be more important.

7 FUTURE WORK

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

The work presented so far is a beginning. There are several avenues which warrant further research. These include further development of the simulator, further validation of the simulator, different operative procedures, streamlining production of patient-specific models and use of the simulator to explore the psychological factors associated with recruitment, training and evaluation of trainees.

7.1 Further development of the simulator

During its development the simulator has been upgraded from using the plug-in Cosmoplayer to Octagaplayer. Although this has led to a slightly less intuitive navigation interface, the advantages of more sophisticated graphics and interface with the browser more than make up for the altered navigation interface. Options for further development include incorporating more sophisticated textures, the introduction of bleeding into the operative field, as well as onto drapes etc. Octaga also has distributed capabilities, thus you could potentially deliver training over the internet with multiple users being present in the same virtual operating room. For the procedures so far implemented this would most likely only be relevant in a developing world situation, as usually there are surgeons with enough experience to guide a trainee. However for novel techniques a networked simulation might prove valuable.

Haptic devices continue to decrease in price and increase in availability. Once they become commonplace rather than simply used within the research arena, they can be integrated into the simulator. Many of the current haptic devices such as the Phantom use the language VRML or X3D for the description of the models, thus make it relatively easy to implement haptics. An open source haptic API is available at www.h3dapi.org. This API uses X3D for descriptions of the model, and Python for logic control. The Bon*e*doc simulator could thus incorporate haptics, by translating the javascript into the appropriate Python code.

The development of a haptic enabled simulator would allow further experiments to determine the extent to which simulators need to incorporate haptics. Similar work is continuing within the aviation industry, and there is an increasing role seen for less sophisticated simulators, as part of the overall training and accreditation environment (Robinson & Mania, 2007). The face validity data for the Bon*e*doc simulator already gathered will serve as a valuable baseline upon which to judge the impact of the introduction of haptics. There is no doubt that haptic devices will increase in sophistication and decrease in cost, and most likely will in the future become part of the standard computer interface.

Another avenue for improving the simulator interface is utilising webcams. Work by groups such as Billinghurst et al (Billinghurst & Kato, 2002) and Morency et al (Morency, Rahimi, Checka, & Darrell, 2002) have developed the use of simple webcams (and more sophisticated stereo camera setups) for obtaining 3-Dimensional location and pose data. These track simple objects including faces (FIGURE 7.1) The Augmented Reality Toolkit uses the VRML format for description of the 3D geometry, allowing the possibility for the trainee to hold a real drill (with markers attached) and use this as input into the simulator.

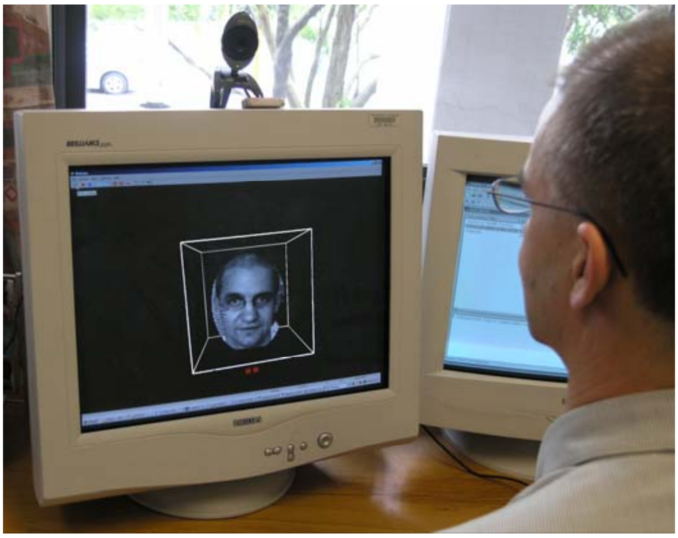

FIGURE 7.1: Watson real time head tracking using a webcam.

7.2 Output from simulator

Further work could be done on upgrading the handling of data outputs from the simulator. As more virtual operations take place, automated analysis of the data would be beneficial, allowing the trainees to compare their performance in real-time with their colleagues' performance. This introduction of competition may invoke the desire to become experts on the simulator, leading to the possibility of enhanced performance in the real world. This has been discussed in further detail in Chapter 2.

7.3 Use as a training tool

Currently the simulator works to provide assessment of the operation, with feedback at the conclusion of the procedure. By extrapolating the trajectory from the entry point to the intercept with the femoral head, and using this intercept and the angle of intersection it is possible to work out where the correct entry point should be. In this manner it is possible to use the simulator as a trainer rather and an assessor.

Care must be taken to provide instructive feedback to the trainee while still allowing them to make independent decisions, and see the result of their performance. This is an issue in real surgery when a senior surgeon finds difficulty in allowing the trainee to operate less than optimally.

If every move is critiqued and the correct steps advised when using the simulator, the trainee will be tempted to rely on this guidance, rather than analysing the steps themselves. Reliance on external guidance is occurring more frequently within medicine, as junior doctors rely more on technology such as x-ray or MRI to reveal the diagnosis, rather than simple history taking and careful physical examination. One method of providing assistance without allowing the trainee to become dependant would be to count how many times the guide-wire angle is changed. Thus when a trainee changes the angle a multitude of times a helpful hint such as “It might be worthwhile to place your entry point further anterior” might help the trainee to progress.

An important part of safe-delivery of healthcare is awareness that there is a constant stream of doctors slowly progressing through their training, and steps need to be taken to ensure that each trainee gets told the message. A potential trap is that topics may be discussed in the literature, allowing those within the profession to up-skill accordingly, and then as this information becomes less fashionable another group of trainees comes through the ranks, and makes the same mistakes. An example of this is the ignorance of the blind-spot in screw placement (Walters & Simon, 1980), and the joint penetration of screws causing chondrolysis (Aronsson et al., 2006).

7.4 Further validation of simulator

The simulator has undergone both face and construct validation. The relatively small number of advanced trainees and their workload has an impact on any study design as well as making it harder to use this group for repeated experiments of validation, without avoiding bias.

Transference of skill from the simulator to the real operating theatre is a validation experiment which is planned. This would take the form of a case-control or cross-over experiment with two groups of basic trainees prior to their first DHS operation. The treatment group would practice on the simulator prior to, or during their first weeks of basic registrar work. Real world performance, such as time of procedure, amount of x-rays, length of incision, number of misplaced drill holes, and final reduction and screw placement could be measured and compared with simulator performance. Potential issues include; the timeframe of acquiring enough trainees at this stage of their training and the fact that they are geographically dispersed around New Zealand (or overseas), the cost of having an investigator monitoring their progress, the impact on the trainees performance by being monitored, and the difficulty of comparing operations of differing complexity. In addition a cross-over design could easily be biased by the effect of the learning curve.

The learning effect could be avoided by using a different cross-over design, with the treatment group practicing a number of times on the simulator and then placing a guide-wire into the femoral head of a cadaver, as opposed to the control group just placing the guide-wire without using the simulator. In addition it would be easier to control the effect of having an observer as the stress of operating on a cadaver is less than operating on a real patient and exact positioning of the screw placement by CT could also be obtained.

7.5 Different operative procedures

This project has demonstrated Bon*e*doc's ability to simulate two operations about the hip. In addition the placement of a distal locking screw in the femur was modelled, albeit without the metrics. There are a myriad of other procedures which could be simulated. These include intramedullary nailing, scaphoid fracture, minimally invasive olecranon wiring, anterior cruciate ligament reconstruction, and pedicle screw fixation.

7.5.1 Intramedullary Nailing

Fractures of the femur and tibia are commonly treated by placing an intra-medullary nail. The Bon*e*doc simulator would be appropriate to simulate this procedure as it again relies on trainee's ability to identify the location of implants in 3-Dimensional space. In fact all the femurs used in the DHS module had a transverse mid-shaft fracture incorporated with this procedure in mind.

During this procedure, a guide-wire is inserted into the femur, with the entry-point just medial to the greater trochanter. The guide-wire is driven down the cavity of the femur, crosses the fracture and is driven further into the cancellous bone at the distal end of the femur. Reamers are then passed over this guide-wire to prepare the cavity for the nail. The nail is then placed, and finally small holes at both ends of the nail are locked with screws to stop the nail from rotating.

All of these steps are suitable for simulation, with some minor modifications. The entry point for the guide-wire is most often palpated but an image intensifier is used to check this position. The simulator could be used for the second part. When the guide-wire is passed down the intramedullary cavity it will mould to the shape of the cavity, which is currently harder for the simulator to recreate. During the procedure the feel of the wire and flexible reamers passing down the shaft and the amount of chatter from the flexible reamers are features which give an indication of the correct width of nail to use. These would not easily be recreated in the simulator currently.

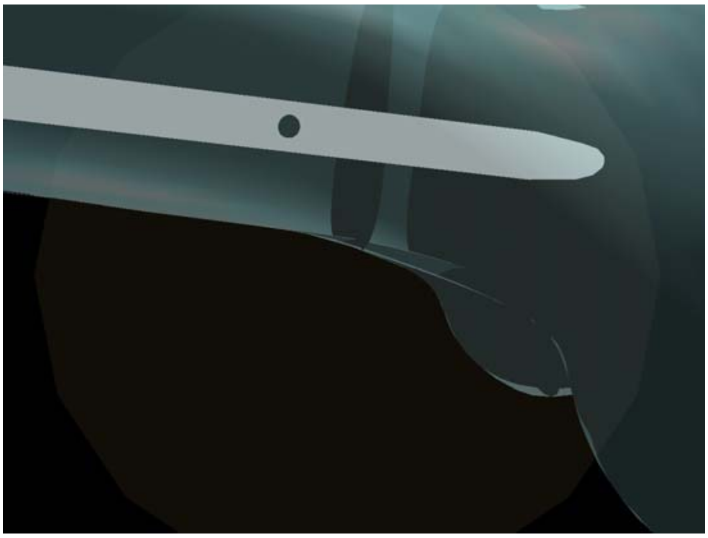

FIGURE 7.2: A virtual x-ray showing intramedullary femoral nail showing the distal locking screw-hole and distal femoral condyles.

An important part of the procedure is reducing the fractures with respect to the rotational alignment. This rotational alignment is hard to assess on an image intensifier view, and the presence of draping, as well as varying amounts of rotation of the hip, can lead to the fracture being fixed in unsatisfactory amounts of internal and external rotation. The measurement of how well fractures are rotationally aligned is already present within the simulator; however during surgery one of the key aspects is palpation of the patella to assess the alignment.

Having passed the reamers, the intramedullary nail is passed, and the distal locking screws are placed. Due to the amount of flex within the intramedullary rod, there are no jigs or guides which are reliable enough to place the distal locking screw accurately. Therefore this part of the procedure relies on image intensifier guidance. The amount of magnification and errors in placement or pose of the image intensifier can make this part of the procedure difficult. An inexperienced radiographer can compound this difficulty. A trainee who can correctly interpret the x-ray image, adjust the position of the image intensifier and subsequently place the distal screw expediently is at a great advantage. This part of the procedure has already been simulated within Bon*e*doc, although further work would need to be done to ensure that the ideal spot moves as the rod is placed according to the trainee's judgment.

7.5.2 Scaphoid Fracture

This is a common fracture involving one of the small carpal (wrist) bones. The blood supply to the scaphoid enters its distal pole, thus displaced fractures of the waist of the bone are prone to avascular necrosis causing subsequent osteoarthritis. These fractures are frequently managed operatively by passing a headless lag screw without a head across the fracture. Complicating factors include the relatively narrow operative view of the bone, the large amount of articular surface and rounded nature of the bone.

FIGURE 7.3: An x-ray showing a scaphoid fracture (arrow).

From a simulation point of view the factors which need special care are the ability to flex, extend and laterally deviate the wrist, exposing different parts of the scaphoid. This movement of carpal bones is complex. Having modelled this, it would be a relatively straight forward task to adjust the parameters of Bon*e*doc's DHS module to record the appropriate placement of the screw. The fact that this procedure is less common makes it ideal for simulation, as qualified surgeons who work in a non-tertiary environment will do a number of these procedures but may well benefit from doing a "dry run".

7.5.3 Olecranon wiring

Olecranon fractures are fractures of the ulna bone at the elbow. These are most commonly treated with a tension band wire construct. This is most commonly performed under direct vision, with usually even the fracture reduced under direct vision. A potential complication involves healing of the skin incision, due to the tendency of the patient to place their elbows on tables. To aide wound healing the ~10cm incision is often made curvilinear avoiding placement of the incision directly over the prominence of the olecranon.

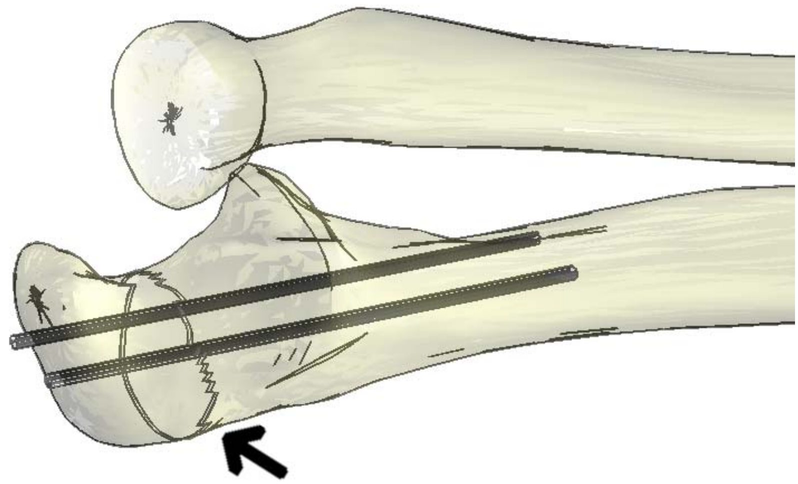

FIGURE 7.4: A simulated view of an olecranon fracture (arrow), showing placement of wires prior to tension-band application. The humerus has not been rendered.

An alternate approach, performed by experienced surgeons is to perform the procedure in a minimally invasive technique; this involves a number of small stab incisions, with the wire passed subcutaneously. This technique relies heavily on the image intensifier for guidance. The steps involved include reduction of the fracture, placing 2 wires parallel to both each other and the shaft of the ulna, and obviously within the bone, and then drilling and passing the figure 8 tension band wire. Apart from passing the tension band wire these steps are all imminently suitable for simulation within Bon*e*doc.

7.5.4 Anterior Cruciate Ligament Reconstruction

The anterior cruciate ligament is one of the ligaments within the knee which has a key role in the final degrees of knee extension. Anterior cruciate ligament (ACL) rupture is relatively common. The surgical repair of the rupture is improving with 66 to 90% of studies having results of "good" or "excellent" patient outcomes (Dye, Wojtys, Fu, Fithian, & Gillquist, 1998), though selecting the correct patient on whom to operate is important. This arthroscopic procedure is rarely performed in New Zealand in the public hospitals, the differing responsibilities to the private patient, in terms of not having a trainee perform the surgery, and the drive to maximise operative efficiency, mean that trainees have less exposure to this technique than other procedures.

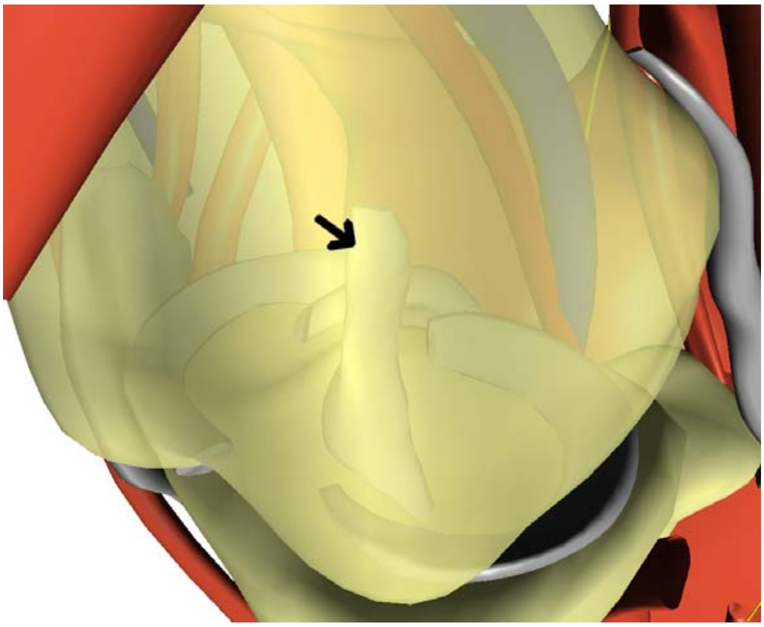

FIGURE 7.5: A view of the knee showing the anterior cruciate ligament (arrow), the femur is rendered translucent

One of the critical factors in ACL reconstruction is placing the graft in the anatomical position (Carlisle, Parker, & Matava, 2007). The ACL is intimately involved with the final extension of the knee, it is composed of 2 main bundles, which are in tension during different stages of extension of the knee. Most surgeons perform a single strand repair, thus causing an approximation of the original anatomy. Due to the ligaments central position along the axis of the knee, there is a large lever-arm effect if the ligament is reconstructed out of this axis, thereby leading to graft failure. The steps within the procedure which would benefit from VR simulation include identification of the correct entry and exit points of the tibial tunnel, and identification of the entry point for the femoral tunnel.

The correct positions for these tunnels are relatively well described (Carlisle et al., 2007). A common error is placing the femoral tunnel on "resident's ridge" This is due to the ridge mimicking that of the correct femoral position. Identification of these points in a VR environment is relatively easy. The exact measurements in terms of distances from the ideal spot, and angles of the various components would provide information which is not available in the real world. However a simulator which is driven by a mouse rather than a haptic device would only teach half the skills. These skills corresponding to basic arthroscopy can easily be taught on a low-cost box trainer.

7.5.5 Pedicle screw fixation

Pedicle screw fixation is spinal surgery performed following spinal fracture, or laminectomy for prolapsed intervertebral disc. The procedure involves dissecting the back muscles off the posterior elements of the spine, thus exposing the bony landmarks of the vertebra. At this point identification of the appropriate vertebral level needs to take place and the image intensifier is often used. The correct starting point on the pedicles is identified, a drill passed down the pedicle, depth measured and tapped and then finally a screw placed. Spinal rods are then attached to these screws. This technique is mostly done under direct vision, however it is reliant on a good 3-Dimensional understanding of pedicles orientation. There is a pattern of changing correct orientation and starting point for these screws due to the changing orientation of the pedicles. Incorrect placement of these screws could result in the screws being placed into a spinal nerve, vascular structures such as the aorta or inferior vena cava, or perhaps outside of the pedicles with resultant loss of position of the surgical construct.

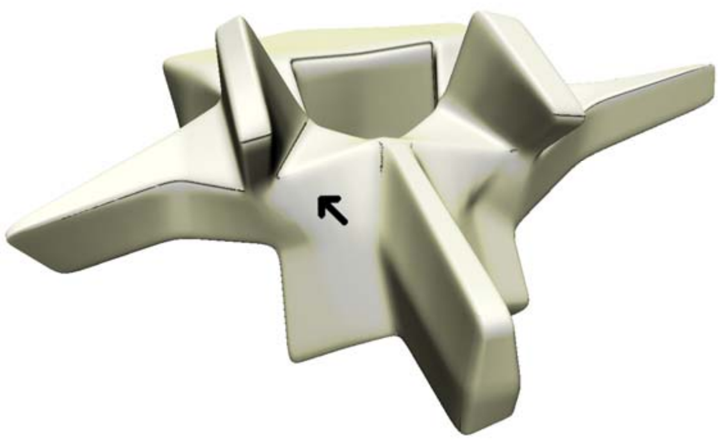

FIGURE 7.6: A virtual lumbar vertebra showing entry point for pedicle screw (arrow).

These steps are easily achievable within the Bon*e*doc simulator. Corresponding measurements of screw accuracy can be viewed and it is possible to see exactly how close the drill-holes were to the relevant anatomical structures. Modelling of the anatomy and ensuring this is as realistic as possible is vitally important to the utility of this module, as the appropriate cues for the surgeon need to be readily identifiable. Although there is a large amount of touch feedback during the procedure, some aspects of feeling can be misleading, thus there is no real endpoint in the tap used to prepare the hole and measure the length of the screw. Due to the cylindrical nature of the drill-hole and the increasing wedge effect the instrument may be far longer than intended and still feel like it is residing in the bone.

7.6 Patient-specific models

The production of patient-specific models has been presented using 2 methods; the host mesh customisation method as used for the DHS module and moulding the bone to conform to a mesh generated from a CT scan in DICOM format as used for the SCFE module. The latter method was suitable given the requirement that only a single example was required for the experiment. As such both of these methods work within the constraints of the projects presented, however for simulation of patients on a non-research platform, further work must be performed in making these options efficient and easy to use.

7.6.1 Host mesh customisation

The host mesh customisation technique has tremendous benefits in terms of modelling the bones and ensuring they have both the appearance of smooth bone. At this stage the process of creating patient specific geometry using the software package CMISS is somewhat demanding for those ignorant of the internal workings of the CMISS software. However this is just a matter of improving and visual interface of CMISS/CMGUI, and progress is being made towards this within the Bioengineering Institute.

Another potential avenue which would be of great benefit is the development of an interface which would allow identification of the target points from 2 (or more) orthogonal x-rays. This would allow the creation of patient specific models without the requirement for CT scans or MRI scans, and their resultant cost and exposure to radiation. This could mean using the profile of the femur to estimate the pose and position of the different bony parts.

Currently the simulator uses surface models of the bones. More realism could be achieved by using a volume model of the bone. The use of volume models is reliant on appropriately powered graphics cards on computers, and for this reason was not pursued in this project. The use of volume type models would allow the virtual x-ray to show the cancellous structure of the bone. Host mesh customisation would provide a readily available solution to providing this level of detail.

In Bon*e*doc patient-specific models require the modelling of fractures. Aspects of fractures which may cause real problems for host mesh customisation include the individual arrangements of the fracture patterns, the acute angles of the jagged bony edges, the angular deformities of the fracture fragments, and the levels of comminution sometimes present in fractures.

7.6.2 CT reconstructions

The advent of spiral CT scanners has yielded a tremendous increase in the resolution of the datasets which can be obtained. These resolutions are currently in the order of 0.6 mm voxels with 1024x1024 pixels. With this increased resolution comes an increase in the sophistication of the reconstructions. Thus from only being able to view CT images in the axial plane, clinical use is made of both sagittal and coronal plane images. Although sufficient for diagnosis, these are still not necessarily adequate for use in the models. The reason for this is that the human eye is both particularly good at filling in detail where needed, as in the case of diagnostic imaging, but also equally good at identifying where there is a break in a pattern, thus pixelated images may destroy the illusion of curved surfaces for bone. The result is that reconstructed CT images initially seem wonderfully smooth, as the ability to play a small mpg segment of the rotation creates the illusion of smoothness in the curvatures, however on zooming into the dataset, the gaps become more evident.

Future work could involve either increasing the capabilities of CMISS with regards to automatic segmentation of volume datasets, or using medical imaging software such as OsiriX (a freeware DICOM viewer www.osirix-viewer.com) which would enable production of an initial patient-specific model. Then with some further smoothing the creation of realistic bone models can occur.

7.7 Psychological factors

Bon*e*doc as presented is suitable for use in a multitude of experiments. It is able to test the effects of different external factors on individual and group performance. The simulator allows testing of these factors on the trainees or surgeons without risking patient safety. As described in this section factors which could be examined are relevant to trainee selection, monitoring of ongoing training, workplace safety as well as providing individuals with feedback such that they can recognise their own particular strengths and weaknesses.

7.7.1 Effect of sleep deprivation

There are a number of papers such as those by Eastridge and Williamson (Eastridge et al., 2003) (Williamson & Feyer, 2000) which show how the effect of sleep deprivation can be compared to alcohol intoxication. These papers suggest that 18 hrs of sleep deprivation is similar to having a blood alcohol level equivalent to the NZ legal driving limit. If these papers are correct, there is a dramatic implication for rostering of trainees, surgeons and junior doctors. If there is a further reduction in work hours, then this has implications for the length of training. Within trainees there is a feeling that their training is already being compromised by this reduction in work hours, though this is debatable. A further study that could be performed is identifying how quickly trainees return to a normal level of operating following a period of sleep deprivation.

7.7.2 Intrinsic vs. Trainable ability for spatial ability

Selection and examination of advanced trainees in surgical specialties like orthopaedics currently does not directly involve tests of spatial ability or dexterity (Bernstein, Jazrawi, Elbeshbeshy, DellaValle, & Zuckerman, 2002). These aspects are currently assessed on the job, by consultant surgeons monitoring the performance of basic or advanced trainees. However there is little standardisation, leaving training committees to modulate the feedback from respective surgeons without any objective measures of allowing for inter-observer bias (Thordarson, Ebramzadeh, Sangiorgio, Schnall, & Patzakis, 2007).

It is apparent that some trainees are less proficient in spatial awareness at the start of the training. On examining the literature it is not readily apparent to what extent an individual is able to up-skill themselves in this ability (Strom, Kjellin, Hedman, Wredmark, & Fellander-Tsai, 2004). Nor is it currently possible to provide the trainees with feedback of how well they perform in this category.

Another experiment could involve comparison between trainees and other groups who require the spatial awareness such as pilots.

7.7.3 Half-life of acquired skills

Commercial airline pilots are required to spend two full days in a simulator per 6 months. This interval has been set by monitoring pilots' performance on the flight simulator, and witnessing a drop-off in performance if the interval is increased to 9 months. Evidence from the anaesthetic literature has shown that residents experience a sharp decline in skills after 6 months (Jameel Ali, Howard, & Williams, 2002). The critical events within these flight simulations are different to the normal flying which is the routine for the pilots. Consequently using the simulator to test for the half-life of acquired skills needs to involve a procedure which they do not routinely perform. For the trainees this could involve the ACL module, however care would be needed to avoid bias from trainees performing the surgery in private.

If these studies did show such an effect this would have implications for those surgeons whose surgical practice only involved intermittent ACL surgery.

7.7.4 The effect of handedness on success of surgery

A paper by Moloney et al (Moloney, Bishay, Ivory, & Pozo, 1994) has shown the effect of the handedness of surgeons on sliding hip screw treatment, with left sided fractures having more complications when operated on by right handed surgeons. Grantcharov et al (Grantcharov et al., 2003) showed that right handed residents made fewer unnecessary movements in laparoscopy than their left handed counterparts.. The degree to which trainees are ambidextrous varies. The Bon*e*doc simulator could be used to examine the extent to which this varies and a description of this attribute could be conveyed to the trainee such that they could be aware of how to avoid errors when operating on their non-optimal side

7.7.5 The effect of senior observers on performance

Every trainee knows that their performance is affected by the presence of their supervising surgeon within the operating theatre. It is hard for surgeons to make objective allowances for this when it comes to rating the performance of trainees. The simulator provides a standardised patient, such that an experiment could be conducted whereby trainees perform surgery with their supervising surgeon present and absent, and these effects analysed in further detail.

7.8 Summary

There are two main paths along which this project can progress further. These are further development of the simulator and further research using the simulator in its current state.

Further development goals include increasing the sophistication of the simulator, simulating new procedures, allowing the simulator to provide a more patient-specific pre-operative "dry run" type of role, and providing cleaner database structures for reporting back to training committees and trainees.

Options for further research include research into psychological factors and further validation. The psychological factors include those attributes inherent within trainees, such as handedness, the effect of observation on performance and the effect of external factors on the trainees, such as sleep deprivation, and the extent to which skills learnt on a simulator diminish over time.

8 CONCLUSION

1. Introduction	2. Background	3. Attitudes towards Simulation	4. Development and Face Validity	5. Construct Validity	6. Slipped Capital Femoral Epiphysis	7. Future Work	8. Conclusion

This thesis describes the conception, development, validation and implementation of a virtual reality simulator for orthopaedics. Bon*e*doc is the first simulator of open rather than arthroscopic procedures which provides results concerning the performance of the trainee in terms which are readily understood. This is due to the fact that the measurements used are the same as those the trainees would use themselves to judge their performance in the real world.

Simulation is a tool which can be used to teach and assess surgical skills. An awareness of the history of simulation and the various strengths and inherent weaknesses common to all simulators will allow better use of this tool in surgical training. Knowledge of the other types of workshops, including animal, cadaveric and simple box type trainers, allows an appreciation for the benefits as well as disadvantages of using virtual reality for simulator training. Simulators which incorporate virtual reality are seen as especially worthwhile in our society with its increasing preoccupation with technology. However training objectives are paramount, and if a simple solution achieves these objectives then its use can be widespread. Simple solutions include box trainers, and low-fidelity (non-haptic) virtual reality simulators. Prior to use as a training or more importantly accreditation/selection tool, simulators need to be validated. There are many forms of validation which a simulator can undergo, some of which are easily performed and others which are almost impossible.

The different simulation technologies were examined, including various haptic devices and methods for creating a stereoscopic view. The difficulties of developing a fully-haptic simulator were explored, but not pursued as the simulator produced would not be suitable for use within the public health system. VRML provided the most appropriate language for coding of the Bon*e*doc simulator due to its integration with the internet, and the Octagaplayer plug-in was selected on the basis that it ran most easily, efficiently and is operating system independent.

A simulator developed in isolation is unlikely to reflect the needs of the surgical community. For this reason a survey of all orthopaedic surgeons and trainees within New Zealand was undertaken. It was gratifying to see that many of the concepts which had already been identified as important for Bon*e*doc were in keeping with the feeling of the orthopaedic community. The lead example of this was that the ability to practice the insertion and angling of a guide-wire was scored the highest, with a median score of 8.4/10. There were differences found between the earlier qualifying surgeons and the more recently qualified, or advanced trainees. One of the more critical examples of this was in relation to whether simulation would impact on their practice and whether simulation could be used for accreditation. The earlier qualifying surgeons felt that this was more likely within the next 5 to 10 years, as compared to the later qualifying surgeons. As the earlier qualifying surgeons are more likely to be on training and education committees and hospital clinical boards this result bodes well for the uptake of simulation.

Although the survey attracted a 68% response rate, this does still leave a significant number of orthopaedic surgeons and trainees whose attitudes are unmeasured. As such the results must be interpreted with caution. Another limitation is the significantly low level of experience with simulators, this reflects the fact that simulation within orthopaedics is in its infancy. However the attitudes sought will still impact on the uptake and relative acceptance of simulation by the community. Every measurement device has an impact on the thing it is trying to measure, and an unplanned result of conducting the survey could be to help propagate the idea of simulation within the minds of the orthopaedic community.

The development of the simulator was based on recreating all the steps required for completion of the image guided procedure of fixing a fractured hip with a sliding screw and plate. By critically examining each part of the procedure, and then implementing a software solution, several concepts surfaced. These concepts included how the entry-point of the guide-wire determines its superior/inferior angulation, relative to the flare of the greater trochanter. Writing names for the various buttons on the virtual image intensifier to move it in different planes highlighted the fact that there was no official terminology for movements of the image intensifier. This lack of agreed terminology is surprising given the importance of communication within the surgical team. An upshot of the simulator could be that clearer communication in the real world would result in less frustration and better performance.

Computers continue to evolve and the performance increases significantly. Finding the balance between the level of detail of objects within the simulator and the speed with which the simulator runs is at times moot. During the programming, it was elected to settle for a more robust, less detailed simulation, due to the limited performance capabilities of the public hospital computers. However the ability to deliver the simulator over the internet affords the ability to increase the realism as computers develop.

The face validity of Bon*e*doc was assessed by means of a questionnaire administered as part of the construct validity experiment. The questions were deliberately taken from the attitude survey in order to try and match how well the simulator would fit the perspective of the orthopaedic community. The majority of trainees felt it provided a realistic view of the operating environment, with a median score of 8.2/10, and thought the 3-dimensional view provided was adequate, with a median score of 7.8/10. In addition the trainees felt the simulator did not need to provide haptics but still allowed practice in the insertion and angulation of guide-wires. As described, this task was also seen by the orthopaedic surgical community as being of greatest importance. The procedures were sufficiently felt to be different enough.

A criticism of the face validity experiment is that the numbers of respondents was relatively low and this could be improved by trialling the simulator on a large number of trainees. The limited number of subjects is a constant problem, however it was felt that the opinions of trainees and surgeons was more valid than utilising groups such as medical students with limited experience of the operative conditions. As more procedures are modelled, the face validity will continue to be measured. These results will act as a valuable comparison to further development of the simulator, perhaps with haptic capabilities.

Ideally the Bon*e*doc simulator would be able to measure real world operating skill. However since there is no measure of real world skill, experience level was chosen as a surrogate. The simulator was able to consistently discriminate between novices and trainees, despite the novices having more computer skills. The accuracy, number of x-rays and speed were significantly different between the novices and trainee surgeons ($p<0.01$, $p<0.05$, $p<0.05$). Intra-articular screw penetration by the medical students occurred 12 times, basic trainees 6 times and advanced trainees twice ($p<0.01$, MS vs trainees).

The lack of statistical significance between basic and advanced trainees was most likely due to a lack of power. A study which has sufficient power to answer this may not be possible within the limited numbers of orthopaedic trainees in New Zealand. Other confounders include the fact that basic trainees are at different levels in their training, as some basic trainees have at least 2 years more experience than their colleagues and some became advanced trainees within 6 months. Importantly the role which natural ability has on the results needs to be further investigated, as very basic trainees may operate more skilfully than senior advanced trainees and vice versa.

One method of overcoming these difficulties is performing a more longitudinal study, and recruiting registrars at the start of their training. The simulator is capable of being deployed nation-wide over the internet, however in order to obtain meaningful results, appropriate organisation needs to be in place. The New Zealand Orthopaedic Association (NZOA) is in an ideal position to contribute to this research, though currently there is not a register of basic orthopaedic trainees. It is envisaged that connections with the NZOA will be strengthened such that over time simulation will be able to aid in the difficult task of selecting trainees, obtaining feedback about aspects of their technical skill, and using this information to direct appropriate training initiatives.

Anecdotally it was interesting to watch advanced trainees operate in both the real and the virtual operating theatres. It was readily apparent that the style and decision making that they displayed were very similar in both arenas. This is somewhat harder to scientifically examine, as there are no current definitions or methods of quantifying aspects such as "confidence in placement of guide-wire", "slickness of making incisions" and "ability to make decisions with limited information".

A second module of the Bon*e*doc simulator was developed with the needs of the advanced trainees in mind. This module simulated percutaneous pinning of a slipped capital femoral epiphysis. This module was tested on all advanced trainees within New Zealand. This module enabled a second look at modelling patient-specific anatomy from volume data such as spiral CT. The advent of the spiral CT and advanced reconstruction methods has yielded more realistic bones, however these technologies do not yet provide bones with enough realism for virtual surgery, hence a combined reconstruction and modelling approach was used.

Final year trainees did not penetrate the hip joint at all, compared to the Year 1, 2 and 3 trainees. However in terms of accuracy of the screw there was no difference detected between year groups. This may be in part due to some bugs within the software which only came to light during the experiment. The experiment's inability to find improved performance by the more senior trainees adds weight to the concept that the effect of natural ability may counteract the improvement from practice. Further experiments on the advanced trainees are planned.

Additionally this experiment showed that there are a number of different styles of operating which result in an accurately placed screw. It also showed that the simulator has the ability to show which trainees are still struggling to identify the 3-Dimensional position of the screw. Finally and importantly this experiment showed that it is possible to use simulation within the normal training weekend environment, which is important as it means the simulator has both the flexibility to be used after hours in an education type role, as well as providing a means of assessing trainees.

Future research and development will see the Bon*e*doc simulator being used to model different surgical procedures as well as explore psychological, work related and education issues relevant to orthopaedic surgical training. Although the procedures described have all been image intensifier based, there is no real requirement to confine it to these procedures, as many orthopaedic procedures involve a process of placing screws, or suture anchors in well-defined anatomical locations, where the 3-Dimensional placement is critical. Issues related to orthopaedic surgical training include the extent to which 3-Dimensional ability can be improved or whether it is innate, the extent to which surgical skill degrades after an intensive training course, the impact of sleep deprivation, and the effect which senior colleagues have on trainees' performance.

In final conclusion, the simulator presented here is hoped to be a worthwhile tool, which is designed not to distance the trainee from their mentor, for that is where the most valuable learning can take place, but rather to provide an opportunity to practice a skill, such that their patients will get the best care possible. For to remove the consultant surgeon as mentor and to replace it with software risks what King Thamus would describe as "they will receive a quantity of information without proper instruction, and in consequence be thought very knowledgeable when they are for the most part quite ignorant."

SURVEYS AND QUESTIONNAIRES

Virtual Reality Surgical Simulation Survey

1. Demographics
a. Please indicate your level of training
□ Specialist □ Advanced Trainee □ Basic Trainee □ Other ……………………
b. Year graduated MBChB …………… Year gained FRACS ………………
c. Gender Male / Female d. Age in years □20s □30s □40s □50s □60s

2. Current exposure to computer based surgical simulation
a. Have you used a virtual reality (VR) simulator? **□YES please fill in below** **□ NO Go to question 3**
NAME of SIMULATOR…………………………………………
WHEN/WHERE …………………………………………
TYPE □ Anesthetic(acls) □ Surgery □ Orthopaedic □ Arthroscopy □ Other …

For each of the following questions please indicate your response by placing a cross on the line.
Example line
Disagree Strongly ——————X—— Agree Strongly

b. How would you critique the simulator
i. Simulation of too simple a task. Disagree Strongly ———— Agree Strongly
ii. Simulator too slow/crashes Disagree Strongly ———— Agree Strongly
iii. Simulator interface too complex Disagree Strongly ———— Agree Strongly
iv. Would only use the simulator once. Disagree Strongly ———— Agree Strongly
v. Task simulated does not relate to my practice. Disagree Strongly ———— Agree Strongly
c. What did you find most valuable in the simulator
……………………………………………………………………………………………
……………………………………………………………………………………………

3. The future of VR surgical simulation
a. It is important to practice a new task in a simulated environment (ie. Without the possibility of endangering patient welfare) Disagree Strongly ———— Agree Strongly
b. Simulation is an effective means to enhance feedback on the learning process? Disagree Strongly ———— Agree Strongly
c. Feedback from a simulator is non threatening? Disagree Strongly ———— Agree Strongly
d. VR surgical simulation will have an impact on my practice in the next 5 years?
Disagree Strongly ———— Agree Strongly
e. VR surgical simulation can be used as an assessment means for accreditation?
In the next 5 years? Disagree Strongly ———— Agree Strongly
In the next 10 years? Disagree Strongly ———— Agree Strongly
f. What sort of validation of a simulator would be needed before you would accept a simulator as a legitimate assessor of a task? □Scientific study in humans □Scientific study in large animals □Expert Opinion □Overseas experience
Please comment ……………………………………………………………………………………
……………………………………………………………………………………………………

4. Computer access
a. How old is your computer □<1year □ 1-3 years □ >3 years □ No computer
c. How often would you access the internet?
□Everyday □ Twice weekly □ Weekly □Fortnightly □ Monthly □Seldom
e. What speed is your connection? □ Modem/Dialup □ Jetstream □ ADSL/LAN (Network)

5. Current methods
a. How do you currently revise anatomy/approaches?
☐ Conference ☐ Journal ☐ CDROM ☐ Orthopaedic text ☐Anatomy text ☐Cadaver Dissection
☐Other …………

6. Perceived requirements of a simulator

a. Must be accessible 24 hours a day.	Not important	________	Very Important
b. Must provide tactile/force feedback (haptics) to surgeon.	Not important	________	Very Important
c. Must provide realistic view of operation.	Not important	________	Very Important
d. Must provide 3D view (usually done with 3D glasses).	Not important	________	Very Important
f. Must allow different scenarios.	Not important	________	Very Important
g. Must test problem solving ability.	Not important	________	Very Important

7. Tasks of simulator

a. Revising anatomy	Not important	________	Very Important
b. Provide feedback on performance	Not important	________	Very Important
c. Pre-operative planning	Not important	________	Very Important
e. practicing angulation/ spatial orientation	Not important	________	Very Important
f. allowing Minimally Invasive Surgery practice	Not important	________	Very Important
g. allow practice of open procedures	Not important	________	Very Important

8. Tasks for simulation
a. For which procedures/approaches would you find a simulation most helpful?
□ Image Intensifier guided □arthroscopy □approaches specify……………………………………
□ Minimally Invasive Surgery specify……………………………………
□ uncommon procedures specify……………………………………

9. Training
a. Training on a simulator should be undertaken frequently ________ Intensively
b. At what stage of your training should you use a simulator?
□Medical Student □Basic Trainee □Advanced Trainee □Surgeon

10. Cost of simulation
a. What is a realistic cost for a surgical simulator.
□<$1-5,000 □$5-10,000 □$10-30,000 □>$30,000
Further Comments (continue overleaf)
……………………………………………………………………………………………………
……………………………………………………………………………………………………
……………………………………………………………………………………………………

Thankyou for taking the time to complete this questionnaire.
Please place the questionnaire in the enclosed envelope and return.
Please contact me if you have further questions.

Dr Phil Blyth
Dept of Anatomy with Radiology, Auckland Medical School
Ph 09 3737599 ext 82779 or 021 2968047 p.blyth@auckland.ac.nz

Skill Levels Posttest   Name……………........

6. Feedback on THIS simulator

For each of the following questions please indicate your response by placing a cross on the line.

a. Should be accessible 24 hours a day. Not important ________________ Very Important

b. Should provide tactile/force feedback (haptics) to surgeon. Not important ________________ Very Important

c. Provides realistic view of operation. Disagree Strongly ________________ Agree Strongly

d. 3D view provided is all that is needed. Disagree Strongly ________________ Agree Strongly

e. Scenarios are different enough. Disagree Strongly ________________ Agree Strongly

f. Tests problem solving ability. Disagree Strongly ________________ Agree Strongly

g. Simulation of too simple a task. Disagree Strongly ________________ Agree Strongly

h. Simulator too slow/crashes Disagree Strongly ________________ Agree Strongly

i. Simulator interface too complex Disagree Strongly ________________ Agree Strongly

j. Would only use the simulator once. Disagree Strongly ________________ Agree Strongly

k. Task simulated does not relate to my practice. Disagree Strongly ________________ Agree Strongly

l. What did you find most valuable in the simulator

……

……

7. Tasks of this simulator

a. Enables revision of anatomy Disagree Strongly ________________ Agree Strongly

b. Provides feedback on performance Disagree Strongly ________________ Agree Strongly

d. Allows practice angulation/ spatial orientation Disagree Strongly ________________ Agree Strongly

e. Allows Minimally Invasive Surgery practice Disagree Strongly ________________ Agree Strongly

9. Training

a. Training on a simulator should be undertaken frequently ________________ Intensively

b. At what stage of your training should this simulator be used?

☐Medical Student ☐Basic Trainee ☐Advanced Trainee ☐Surgeon

10. Cost of simulation

a. What is a realistic cost for THIS surgical simulator.

☐<$1-5,000 ☐$5-10,000 ☐$10-30,000 ☐>$30,000

Further Comments (continue overleaf)

……

……

Thankyou for taking the time to complete this questionnaire.
Please place the questionnaire in the enclosed envelope and return.
Please contact me if you have further questions.

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Dept of Anatomy with Radiology, Auckland Medical School
Ph 09 3737599 ext 82779 or 021 299 2237 p.blyth@auckland.ac.nz

2

Skill Levels Pretest   Name……………........

1. Demographics
a. Please indicate your level of training

☐ Specialist ☐ Advanced Trainee ☐ Basic Trainee ☐ Other ……………………
b. Year graduated MBChB ……………… Year gained FRACS ……………… Med Student Year …….
c. Gender Male /Female d. Age in years ☐<20 ☐20s ☐30s ☐40s ☐50 s ☐60s

2. Previous exposure to computer based surgical simulation
a. Have you used a virtual reality (VR) simulator? ☐**YES please fill in below** ☐ **NO Go to question 3**
NAME of SIMULATOR…………………………………………..
WHEN/WHERE …………………………………………
TYPE ☐ Anesthetic(acls) ☐ Surgery ☐ Orthopaedic ☐ Arthroscopy ☐ Other …

3. Computer Experience
a. How often would you play computer games / playstation /xbox

☐Everyday ☐ Twice weekly ☐ Weekly ☐Fortnightly ☐ Monthly ☐Seldom
Please comment ……………………………………………………………………………………………

………

b. How would you describe your level of computer knowledge.

Complete novice ―――――――――――― Expert

4. DHS Experience
a. How often would fix a fractured NOF with a DHS type system
☐ Twice weekly ☐ Weekly ☐Fortnightly ☐ Monthly ☐Bimonthly ☐Annually ☐Never have
Please comment ……………………………………………………………………………………………

………

5. Computer access
a. How old is your computer ☐<1year ☐ 1-3 years ☐ >3 years ☐ No computer
b. How often would you access the internet?
☐Everyday ☐ Twice weekly ☐ Weekly ☐Fortnightly ☐ Monthly ☐Seldom
c. What speed is your connection? ☐ Modem/Dialup ☐ Broadband ☐ Network

INSTRUCTION MANUAL FOR DHS MODULE

Bonedoc

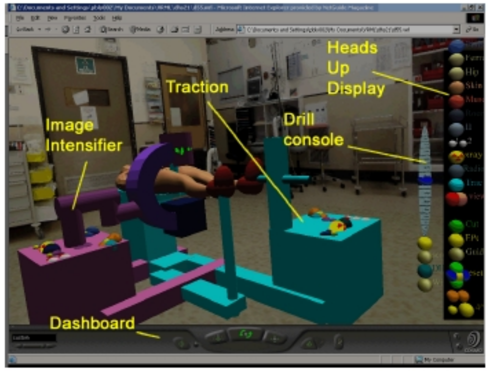
Admission to hospital following a hip fracture (properly called fractures of the neck of femur) is a common occurrence. In the period 1988 to 1999 at least 32 000 patients were admitted to New Zealand hospitals (Stephenson et al 2003).

These fractures are commonly fixed with a sliding screw and plate (Dynamic Hip Screw). This surgical procedure is performed under x-ray guidance using an image intensifier (II), which gives the surgeon digital images of the location of the drills and screws within the operating theatre.

The decisive steps within this procedure are as follows.

1. Obtain the correct x-ray views of the fracture. Usually 2 views taken at right angles to each other are used.
2. Reduce the fracture i.e.. Aligning the bone fragments to restore the normal anatomical position.
3. Make a skin incision.
4. Drill a guidewire from the lateral side of the shaft of the femur into the central part of the femoral head.
5. Place the definitive sliding screw over this guidewire, with the plate lying parallel to the shaft of the femur.
6. Place further screws which anchor the plate to the side of the shaft of the femur.

Navigating around the operating theatre.

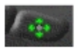
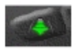
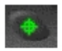


This can be done in two main ways.

1. Using the dashboard

To examine objects in a 3D world, click the **Rotate**, **Pan**, or **Zoom** button and then drag the pointer in the Cosmo Player window. Once you click a control, it stays selected until you click another.

(More detailed help is available by clicking on help button on the dashboard.)

Rotate		Click and then drag to rotate an object.
Pan		Click and then drag to pan right, left, up, or down.
Zoom		Click and then drag up to zoom in or drag down to zoom out.
Seek		Click this then on any part of the scene to zoom in to that part.
Viewpoint		Click this to select from the list of viewpoints available, or press Page Up/Down.

2. Using the Heads Up Display (HUD)

Click to switch to the Radiographers viewpoint in order to change the position of the image intensifier

Click to switch to the Traction adjusting viewpoint in order to change the traction settings to reduce the fracture.

Click the left circle to SET the custom view, or the right circle to VIEW the custom view (after an x-ray is taken you are returned automatically to this custom view).

Overview of Buttons

When you place the mouse over a button which you can press, the pointer changes to a starburst.
There will then be a description of what that button does in the footer of the webpage.

RED buttons store the angles or positions in the simulators memory.
WHITE buttons recall the angles or positions which are in the simulators memory.
YELLOW buttons reset the angles or positions to the startup position.

3

Step 1

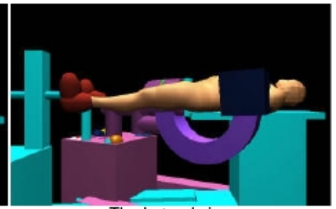
Steps to Operate

1. Obtain the correct x-ray views of the fracture.

Suggested views have already been stored in the simulators memory, you can just click either of the WHITE buttons on the HUD.

Alternatively you can select your own position and orientation for the Image Intensifier. You should obtain an AP and a Lateral x-ray.
The Image Intensifier should look like this.

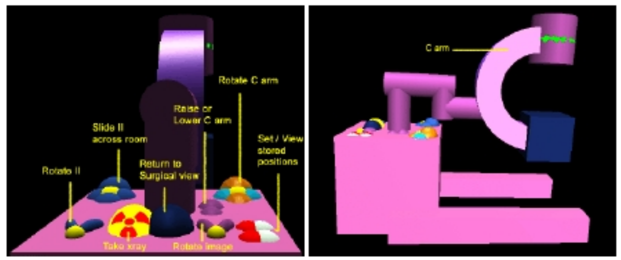
The AP view



The Lateral view

A. Ensure the x-ray machine (Image Intensifier) is in the theatre. You may need to click the II button on the HUD

B. Change to the radiographers viewpoint. By clicking the Radiog button.



C. The buttons on the left side move the whole II machine around the operating theatre.
The buttons on the right side move the C arm.
Once you have rotated the II and its C arm to the correct position, click and hold the x-ray button to view the x-ray.

4

Step 1

The image called an "AP view of the hip" should look something like this.

D. When you are happy with the view obtained click the RED button to store that position.

E. Repeat the process to obtain a "lateral view of the hip", which looks like this.

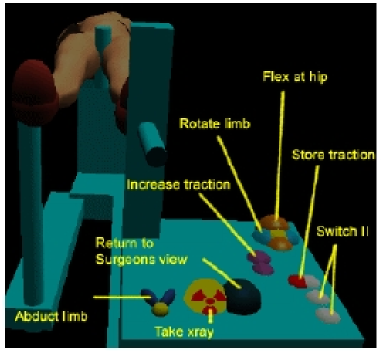
F. You may move the II to these stored positions by pressing on the appropriate WHITE buttons on the HUD and traction console.

5

Step 2

2. Reducing the fracture i.e.. Aligning the bone fragments to restore the normal anatomical position.

A. Change to the traction console view. By clicking the Trac button.



B. Adjust the various angles on the traction view by clicking the appropriate button.
You should adjust the abduction, increase traction, rotate limb and flex at the hip.
To see the effect of your traction adjustment, click and hold the x-ray button to see the view, you should also switch II views.

C. If you are happy with the traction adjustments you can store them by clicking the RED button. Then return to that adjustment, by clicking the adjacent WHITE button.

D. The purpose of the traction is to align the boney fragments to restore the anatomical relationship, which you can see in the above x-rays.

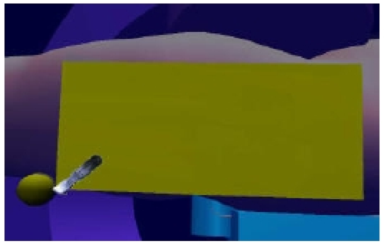
6

3. Making a skin incision .

A. Return to surgical view by clicking the Return to Surgeons view button.

B. Click the Skin button, this places the sterile plastic drape.

C. Select "incision" from the viewpoint list on the dashboard. You will be able to see a feint outline of the femur (thigh bone).

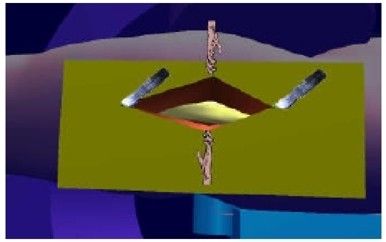


D. Click the orange button to pick up the scalpel. Click and drag this scalpel to the left hand side of where you would like to make your incision, and leave it there.

E. Click the orange button to pick up the end scalpel. Click and drag this scalpel to the right hand side of where you would like to make your incision.

F. Click the orange button to pick up the lower retractor. Click and drag this retractor to the place where you want the skin edge to be pulled down to.

G. Click the orange button to pick up the higher retractor. Click and drag this retractor to the place where you want the skin edge to be pulled up to.



H. Double click the Cut button on the HUD. This makes the incision and retracts the skin edges.

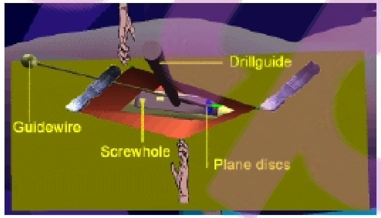
I. You can make adjustments to either of the scalpels or retractors at any time, then double click the Cut button to see your adjustments.

Step 4

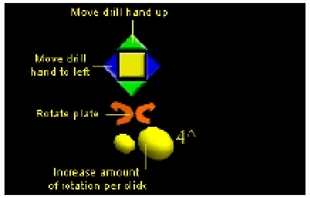
4. Drilling a guidewire from the lateral side of the shaft of the femur into the central part of the femoral head.

A. You can now see the femur in the depth of your wound. Zoom in and rotate till you are happy that you can see enough of the bone. You may need to enlarge your incision.
Click the RED button called view on the HUD. This locks in this view as the Custom viewpoint, so you return to it after taking an x-ray.

B. Position your mouse over the bone, and then click to select the starting point for your drill. The drill guide and guidewire will automatically appear.
The drill console will also appear.

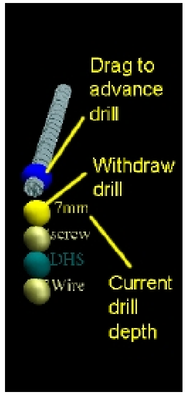


C. Rotate the drill guide to find the angle which will place the guidewire in the centre of the femoral head.
This is done by pressing the buttons on the lower end of the HUD.
You will note that the colours relate to the colours on the plane discs.
If you want to return to the default rotation click the YELLOW button in the centre.



Step 4

D. Drag the blue slider to advance the drill. You will see the current depth displayed in mm.



E. Check the position of your Guidewire by taking x-rays in both planes. You can use the buttons on the HUD to switch II positions.

F. If you make a mistake click the YELLOW button to withdraw the drill, then you can change the angle.

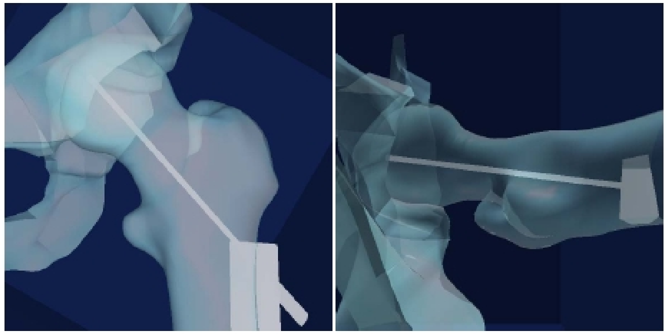
G. If you want to choose a new entry point, click the YELLOW button called EPt on the HUD, then click your new point on the bone.

H. When you have the correct angle, advance the drill till it is 5mm short of the articular surface of the head.

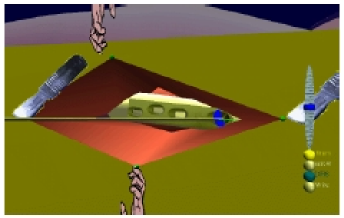
Step 5

5. Place the definitive sliding screw over this guidewire, with the plate lying parallel to the shaft of the femur.

A. You should now have the guidewire in a position that looks like this.



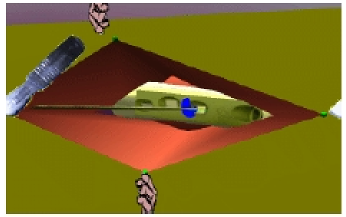
B. Click the DHS button on the drill console. This will place the definitive screw over the guidewire and the plate down the femur.



Step 6

6. Placing further screws which anchor the plate to the side of the shaft of the femur.

A. Click the EPt button to change the entry point, then click on bone in the center of one of the holes on the plate.

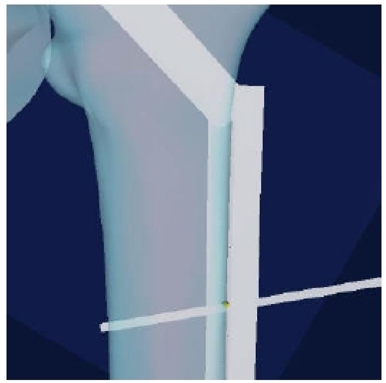


B. Now rotate the drill so that it lies perpendicular to the bone, using the same controls on the HUD that you placed the original guidewire.

C. To obtain an x-ray image of where you are drilling, you will need to move the Image Intensifier. (see step 1).

D. If you make a mistake in the angle or position follow the instructions for step 4.

E. The x-ray should look something like this..



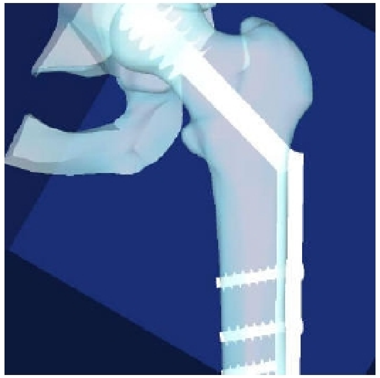
F. Click the screw button on the drill console, to fill this with a cortical screw.

G. Repeat steps A-F for the other screws.

Step 7

7. Finish the procedure

If your x-ray looks like this....



you have finished.

A. Click the Finish button on the HUD to calculate your score.

WELL DONE.

Tips and Tricks

1. If you seem to be standing on your head, press the Page Up key.

2. If the preferences on the dashboard are set correctly, you should be able to....
   Hold CTRL and drag to Zoom.
   Hold ALT and drag to Pan.
   Right click to Seek.

How to get a high score

1. Reduce the fracture anatomically.

2. Place the center of the DHS screw in the apex of the femoral head, 5mm short of the articular surface. (as on the xrays above).
   If you drift from that position, it is best to drift posteriorly (towards the ground) and inferiorly (towards the feet).
   Do not place the DHS screw across the hip joint!

3. Align the plate on the side of the bone, if this plate sits off the bone, your score will suffer.

4. Make a small incision. You may move the retractors as often as you like, but you will be penalised each time you move the scalpels.

5. You are penalised on each unneccesary drill hole. The depth you drill is measured, so do not wildly overdrill till you know the angle is correct.

6. Take less x-rays, however you need to take as many as will help to guide your drilling.

7. Reduce the fracture to the anatomical position fast. You do not want the anaesthetic to lose effect.

8. Operate quickly.

COMMANDS FOR CREATION OF NEW FEMURS

C.1 Steps for using host mesh to create patient specific models for inserting into simulator

This procedure uses data from the "faro arm" to create VRML files of subcapital, basicervical and intertrochanteric fractures.

Using files in directory called ./mayfemurs.

1. Copy .mtr file (output from faro arm) to ./mayfemurs folder.

2. Convert format of .mtr to .ipdata file manually.

3. Change y coordinate to negative values (if need to flip right to left).

4. Convert format of .ipdata to .exnode format and rename file to fem4b.exnode (need to add group name, field and nodes.

5. Use CMGUI and commandfile ./2lineup.com to rotate and translate points closer to target pts. (if problem with <cr> in fem4b, use cmgui command *gfx read node fem4b* then *gfx write node fem4b* and manually remove <cr>

The landmark and target point are detailed in TABLE C.1

Point	Landmark and Target Point
1.	Anterior point of femoral head
2.	Superior point of greater trochanter
3.	Distal most point of lateral condyle
4.	Distal most point of medial condyle
5.	Apex of femoral head
6.	Lateral most point of greater trochanter
7.	Posterior point of femoral head
8.	Anterior point of proximal femoral neck
9.	Posterior point of proximal femoral neck
10.	Medial point of lesser trochanter
11.	Posterior point of medial condyle
12.	Posterior point of lateral condyle
13.	Adductor tubercle
14.	Lateral point of lateral condyle
15.	Anterior point of lateral condyle
16.	Anterior point of medial condyle
17.	Medial point of femoral head
18.	Superior point of femoral head
19.	Superior point of proximal femoral neck
20.	Inferior point of proximal femoral neck
21.	Lateral point of mid-shaft femur
22.	Anterior point of mid-shaft femur
23.	Posterior point of mid-shaft femur
24.	Medial point of mid-shaft femur

TABLE C.1: Landmarks and target points for the femur.

6. Within CMGUI *gfx edit graph femur_projection apply*

7. *gfx wri no group femur_projection fem4b2*

8. Convert format of fem4b2.exnode to femur_projection_4.ipdata by removing group, field, and node.

9. From command line *cm run_example*

10 From commandline *cmgui show_host*

11 Within CMGUI *gfx wri no group femur_cust femur_cust*

12 Copy femur_cust.exnode to win_d/2fracture/

13 Within CMGUI shift nodes to create customised look to fracture

13a. From command line *cmgui 2renum* (renumbers nodes to create surface)

13b. Manually change groupname in femur_cust_orig.exnode and exelem to femur_cust_orig

13c. From command line *cmgui 2editnode*

13c Within CMGUI *editnode 'femur_cust"* and then alter the femur_cust nodes

13d. When satisfactory within CMGUI *gfx edit graph femur_cust apply*

13e. Then type *gfx wri no group femur_cust 22subc* or 22basic or 22intert to create each fracture accordingly where 22 is the name of the new femur created

14 Run perl script 2frac.pl having changed $femno to "22" and will generate subcapital, basicervical and intertrochanteric fractures in current folder

15 Run perl script makeproto4.pl to create protos for these

16. Manually change file header

C.2 An alternative method for creating overlapping fractures involves

13a.From command line *cmgui 2subcapitalise* (change $femno and then creates separate head and prox)

13bi. Manually change groupnames from femur_cust to 31heads and 31proxs

13bii. Change groupname in femur_cust_orig.exnode and exelem to femur_cust_orig

13c. From command line *cmgui 2editnode* then *editnode 'heads"* and then alter the head nodes

13d. When satisfactory within CMGUI *gfx edit graph femur_cust apply*

C.3 Steps for placing meshed femur into theatre space and obtaining planes and sweetspots for accuracy calculations

1 Use ./tools/rotatehead9.wrl to overlay new head roughly onto generic femoral head. Check head2 is in slave section, then copy this transformation into the protos for 23headb.wrl 23proxb.wrl 23 distb.wrl etc

2. Use ./tools/rotatehead9.wrl to plot in planes for midpt with head2 out of slavery.

3. Then rotate sweetorient and click the button labelled ASS to obtain final values for plane1f, plane2f, plane3f, sweetspotf and sweetorientf which plug in to appropriate javascript file eg PatA.js

C.4 Steps for creating 10 femurs in different positions

The position to which the traction table must be moved in order to anatomically reduce the fracture is simply performed by adjusting the appropriate cell in the excel spreadsheet HEADOUTrotations.xls, then copying the outputted section in the lower half of the spreadsheet into the appropriate javascript file for that femur. Eg PatA.js

Copy from HEADOUTrotations.xls into HEADOUT of 66.wrl

C.5 To output files from CMGUI via BLENDER to VRML

Many of the bone models within the anatml database are volume models, therefore only the surfaces must be exported, otherwise there are inconsistencies when viewing bones translucent.

Consequently these cmgui commands allow export of a wavefront .obj file which can be further manipulated within blender, and then finally exported for use within VRML.

1.Within CMGUI

gfx re no e:/anatml2/radius

gfx re elem e:/anatml2/radius

gfx cre win

gfx mod g_e radius_right surfaces exterior

gfx mod g_e radius_right lines invisible

gfx export wave file radius_right

2. Within Blender

File>import> wavefront

Manipulate as required

File>export VRML

3. Within text editor (such as pspad.exe)

Change *NavigationInfo* { …} to

NavigationInfo { *headlight FALSE speed 10 type ["EXAMINE", "ANY"] avatarSize [0.25, 1.75, 0.75]*}

Search and Replace "*solid TRUE*" with "*solid FALSE creaseAngle 3*"

This step allows objects to be rendered smoothly, and not suffer from rendering of internal surfaces.

Appendix D

CALCULATION OF SCREW PLACEMENT ACCURACY

In order to calculate the displacement of the screw tip from the sweet spot of the femoral head, several transformations are required.

Firstly the position of the correct spot within the femoral head. This is the point at which a perfectly placed lag screw's tip should reside. This is defined as 5mm from the fovea of the femoral head, directly in the line of the femoral neck.

Secondly the pose of the femoral head/proximal fragment within the world. This position is altered by the pose of the femoral head within the virtual world. This pose is set as part of the parameters for that particular operation. At this stage the pose of the femoral head does not change as the traction is adjusted, this is to make this part of the procedure easier. In reality adjusting the traction without first distracting the fragments may alter the position of the head, though the physics of this interaction have not been described sufficiently to incorporate. Thus the output from the traction adjustment does not change the orientation of the femoral head.

Thirdly the pose of the distal fracture fragment. This pose is governed by the various adjustments of the traction console. Thus the rotations in each of the three planes, and the translation are used in this calculation.

Fourthly the position of the entry point is identified by a TouchSensor node with which the cosmoplayer browser plug-in identifies the position on the surface of the femur where the mouse is pointing and outputs this into the appropriate script. The angle of trajectory is then adjusted by altering the drill hand using three adjustment buttons. The depth that is drilled is then obtained by how much a widget is advanced. From this the final tip placement within the adjusted femoral head is calculated.

This is represented in the VRML by

```
DEF Femoral_Head Transform {
        DEF Sweetspot Transform { }
}
DEF Distal_Fragment Transform {
```

```
    DEF Entry_Point Transform {
        DEF Trajectory Transform { }
    }
}
```

From this the displacement between the sweet spot and the final screw-tip position can be calculated.

Each of these transformations (combined translations and rotations) can be defined where

A. The ideal point

B The transformation of ideal point spot within the femoral head.

C. The transformation of the femoral head within the world

D. The transformation of the proximal fragment.

E. The position of the entry point

F. The trajectory and distance of the screw.

G. The final screw tip.

Utilizing matrix multiplication to calculate these

So the position in the world view of the final screw tip is.

F= E x D x C

And the position of the sweet spot is

A= B x C

Thus AF is the vector from A to F. In order to describe the displacement in terms of anterior, inferior and depth, this vector is broken down into x, y and z components, with the axis given by the axis of the femur.

The Tip-Apex Distance within the paper by Baumgaertner (Baumgaertner 95) is defined as "*the sum of the distance, in millimetres, from the tip of the lag screw to the apex of the femoral head, as measured on an anteroposterior radiograph and that distance as measured on a lateral radiograph, after correction has been made for magnification.*" Within the simulator the Tip-Apex Distance can be calculated using Pythagorean Theorem to determine the distances from the apex (5mm in the long direction from the ideal spot) to the screw in these planes.

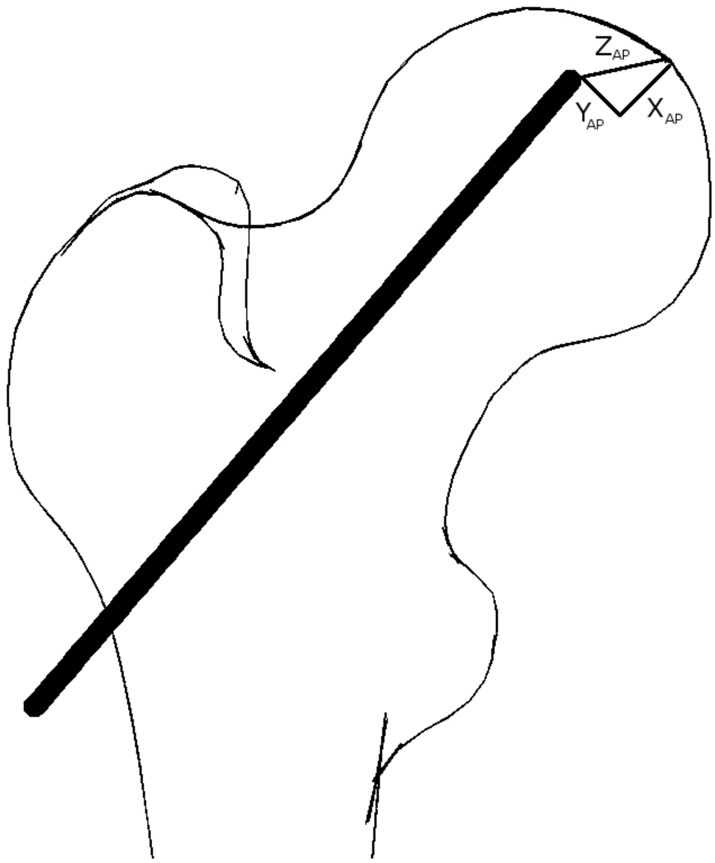


FIGURE D.1: Calculating the distance from the apex of the head to the tip of the lag screw on the AP x-ray.

On FIGURE D.1 Z_{AP} is the hypotenuse of the distances where Z_{AP} is in the anteroposterior plane, X_{AP} is the distance in the short axis and Y_{AP} is the distance in the superoinferior plane. And Z_{lat} is the hypotenuse of the distances where Z_{LAT} is the superoinferior plane and X_{LAT} is the distance in the short axis and Y_{LAT} is the distance in the anteroposterior plane. Within the simulator there is no need to allow for magnification from the image intensifier, as these are calculations rather than measurements on an image.

From Pythagorean Theorem where $Z^2 = X^2 + Y^2$

$$TAD=\left(\sqrt{\left(\left(X_{AP}+5\right)^2+Y_{AP}{}^2\right)}\right)+\left(\sqrt{\left(\left(X_{LAT}+5\right)^2+Y_{LAT}{}^2\right)}\right)$$

Thus the TAD can be readily calculated, rather than requiring the trainees to measure it and perform the calculation themselves.

LINE-PLANE INTERSECTION

Another method described in the literature is measuring the location of the screw with respect to the centre of the femoral head (Parker, 1992).

In order to correlate the findings from the simulator with real measurements, it is necessary to calculate the Line-Plane Intersection. This is the intersection between the line running down the centre of the screw (or guide-wire) and the plane represented either by the centre of the femoral head in both AP and lateral views in the case of the femoral neck fracture, or the plane of the physis in the case of the SCFE. Utilizing the method of calculating the intersection between a plane and a line, the simulator is able to objectively score this measurement.

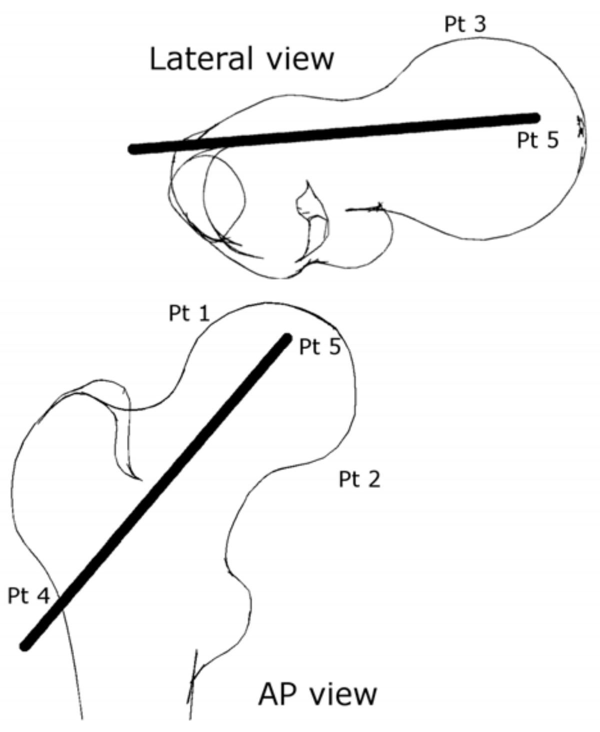


FIGURE E.1: Points used to calculate intersection between screw and mid-point of femoral head.

If the plane through the femoral head is determined by three points (FIGURE E.1); the most superior point on the head (Pt 1), the most inferior point of the head (Pt 2) and the most anterior point of the head (Pt 3). If the line of the centre of the compression screw passes between the entry point (Pt 4) and the tip of the screw (Pt 5), which is calculated from the trajectory and the length of the screw.

The coordinates of Pt 1 can be written as (x_1,y_1,z_1), Pt 2 can be written as (x_2,y_2,z_2) and so forth.

Then the intersection between the screw and the plane through the femoral head can be calculated by solving four simultaneous equations.

$$0=\begin{vmatrix} x & y & z & 1 \\ x_1 & y_1 & z_1 & 1 \\ x_2 & y_2 & z_2 & 1 \\ x_3 & y_3 & z_3 & 1 \end{vmatrix} t \tag{E.1}$$

$$x_6 = x_4 + \left(x_5 - x_4\right) t \tag{E.2}$$

$$y_6 = y_4 + \left(y_5 - y_4\right) t \tag{E.3}$$

$$z_6 = z_4 + \left(z_5 - z_4\right) t \tag{E.4}$$

Thus yielding

$$t= - \frac{\begin{vmatrix} 1 & 1 & 1 & 1 \\ x_1 & x_2 & x_3 & x_4 \\ y_1 & y_2 & y_3 & y_4 \\ z_1 & y_2 & z_3 & z_4 \end{vmatrix}}{\begin{vmatrix} 1 & 1 & 1 & 0 \\ x_1 & x_2 & x_3 & x_5 - x_4 \\ y_1 & y_2 & y_3 & y_5 - y_4 \\ z_1 & z_2 & z_3 & z_5 - z_4 \end{vmatrix}} \tag{E.5}$$

To calculate t we need to calculate the determinants for the numerator and denominator of Equation D.5.

The determinant for a 4x4 matrix is

$$\left|\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \\ m & n & o & p \end{bmatrix}\right| = a\left|\begin{bmatrix} f & g & h \\ j & k & l \\ n & o & p \end{bmatrix}\right| - b\left|\begin{bmatrix} e & g & h \\ i & k & l \\ m & o & p \end{bmatrix}\right| + c\left|\begin{bmatrix} e & f & h \\ i & j & k \\ m & n & p \end{bmatrix}\right| - d\left|\begin{bmatrix} e & f & g \\ i & j & k \\ m & n & o \end{bmatrix}\right|$$

where the determinant for a 3x3 matrix is

$$\left|\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}\right| = a\left|\begin{bmatrix} e & f \\ h & i \end{bmatrix}\right| - b\left|\begin{bmatrix} d & f \\ g & i \end{bmatrix}\right| + c\left|\begin{bmatrix} d & e \\ g & h \end{bmatrix}\right| \tag{E.7}$$

and the determinant for a 2x2 matrix is

$$\left|\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right| = a*b-c*d \tag{E.8}$$

Thus for the case of the numerator in Equation 13.5

$$\begin{vmatrix} a=1 & b=1 & c=1 & d=1 \\ e=\text{superior.x} & f=\text{inferior.x} & g=\text{anterior.x} & h=\text{entryptf.x} \\ i=\text{superior.y} & j=\text{inferior.y} & k=\text{anterior.y} & l=\text{entryptf.y} \\ m=\text{superior.z} & n=\text{inferior.z} & o=\text{anterior.z} & p=\text{entryptf.z} \end{vmatrix} \tag{E.9}$$

numerator=(a(f(kp-lo) - g(jp-ln) + h(jo-kn)))- (b(e(kp-lo) - g(ip-lm) + h(io-km)))+ (c(e(jp-ln) - f(ip-lm) + h(in-jm)))- (d(e(jo-kn) - f(io-km) + g(in-mj))) (E.10)

and the denominator of Equation 13.5 can be calculated similarly whereby

$$\begin{vmatrix} a=1 & b=1 & c=1 & d=0 \\ e=\text{superior.x} & f=\text{inferior.x} & g=\text{anterior.x} & h=(\text{screwtipf.x-entryptf.x}) \\ i=\text{superior.y} & j=\text{inferior.y} & k=\text{anterior.y} & l=(\text{screwtipf.y-entryptf.y}) \\ m=\text{superior.z} & n=\text{inferior.z} & o=\text{anterior.z} & p=(\text{screwtipf.z-entryptf.z}) \end{vmatrix} \quad \text{(E.11)}$$

denominator=(a(f(kp-lo) - g(jp-ln) + h(jo-kn)))- (b(e(kp-lo) - g(ip-lm) + h(io-km)))+ (c(e(jp-ln) - f(ip-lm) + h(in-jm)))- (d(e(jo-kn) - f(io-km) + g(in-mj))) (E.12)

Then to calculate t is simple division of Equations 13.10 and 13.12 and substitution into Equations E.2-4.

The intersection of the line and plane has been adapted from Weisstein, Eric W. "Line-Plane Intersection" From MathWorld--A Wolfram Web Resource.

http://mathworld.wolfram.com/Line-PlaneIntersection.html

The calculation of the determinant is described at

http://easyweb.easynet.co.uk/~mrmeanie/matrix/matrices.htm

CALCULATION OF SCREW ANGLE ERROR

The lag screw is supposed to be placed orthogonal to the plane of the physis. It is possible to calculate the deviation from this plane for screws which are not placed orthogonal. This deviation can be measured in either the anterior/posterior or superior/inferior planes.

The simulator calculates the plane of the physis as described in Appendix E, with the anterior/posterior axis, a superior/inferior axis aligned with the physis. The intersection of the trajectory with the physis is also described in Appendix E, and the calculation of the location of the screw-tip is described in Appendix D. Once both of these locations is described within the same local co-ordinate system (that of the physis), calculation of the angles is performed according to Pythagorean Theorem.

For deviation in the superior plane only the short/long and superior/inferior axes are used,

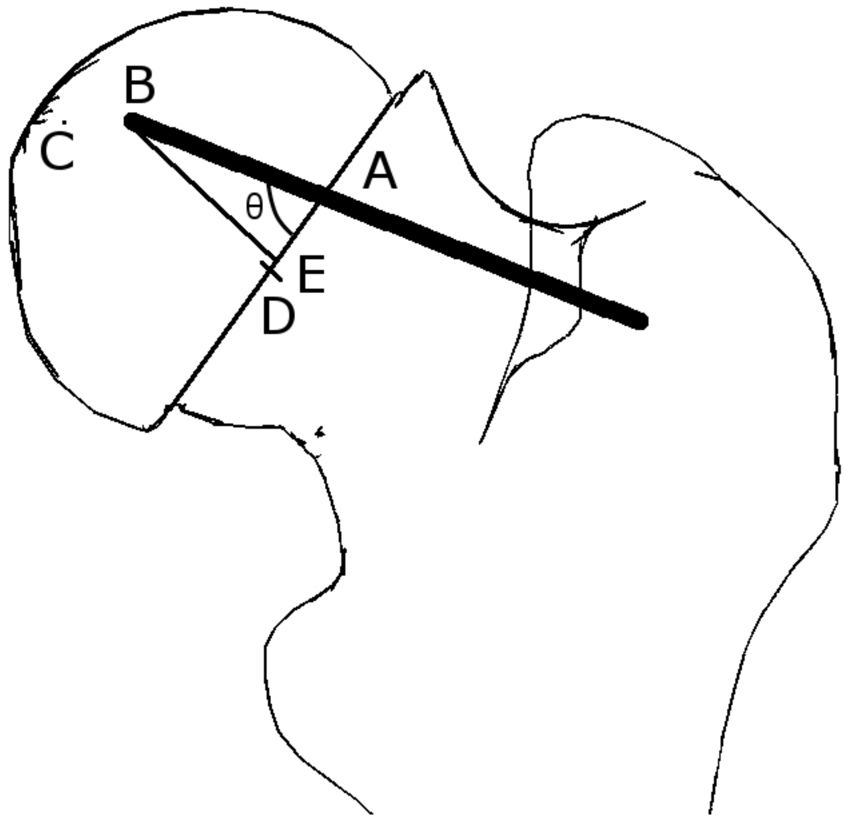


FIGURE F.1: Points used to calculate the screw angle error in the superior plane.

Pt A is the intersection of the screw with the physis. This is calculated as per Appendix E.

Pt B is the tip of the screw. This is calculated as per Appendix D.

Pt C is ideal spot. This is calculated as per Chapter 4.

Pt D is the point on the physis where a line drawn orthogonal to the physis intersects with the ideal spot.

Pt E is the point on the physis where a line drawn orthogonal to the physis would intersect with the tip of the screw. As the coordinate systems for the physis and the ideal spot are equivalent, this point amounts to the deviation of the tip of the screw in the superior axis.

Thus the angle θ in the superior plane is given by

$$\text{Sin}\ \theta = \frac{\text{opposite}}{\text{hypotenuse}} \tag{F.1}$$

$$\text{Sin}\ \theta = \frac{\text{distance BD}}{\text{distance AB}} \tag{F.2}$$

$$\text{distance BE} = \text{distance CD} - \text{Distance CB (in plane along the line CD)} \tag{F.3}$$

CALCULATION OF ERROR TRAJECTORIES

Error trajectories are calculated to identify different styles of operating amongst trainees. These trajectories are one way to describe mathematically how easily trainees are able to identify the projected trajectory of a guide-wire and then make the appropriate correction to either the entry-point position or the angulation of the guide-wire. An analogy in golf is that rather than simply tallying up the number of shots taken for each hole, a map of the position of each shot is taken, in addition to calculating the distance which the ball travels. Two golfers may score 5 for a particular hole, but one of the balls may have travelled twice as far or there may have been 3 shots on the green.

The error trajectories can be calculated because the entry point, angle and length of each mistake are automatically recorded by the simulator, allowing localisation of the tip of the mistakenly placed guide-wire. From these locations, it is then possible to calculate the vector A from the ideal spot to this tip.

This vector can then be broken down into the deviation in three axes, the deviation in the superior/inferior plane can be visualised on the AP view as the distance from the central line to the tip of each guide-wire, as seen in Figure G.1. On this diagram the reference point is to the middle of the guide-wire, as they have been drawn parallel to the central axis for simplicity.

The depth component is not included in this trajectory calculation (though the total depth of the drills is recorded).

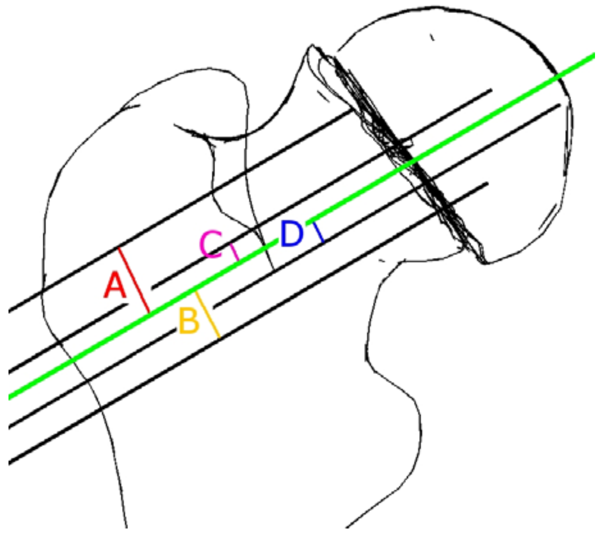


FIGURE G.1: AP view showing four mistakes with increasing depth, and the central axis (green line).

Similarly the vector in the anterior/posterior plane can be calculated off the lateral view, as seen in Figure G.2.

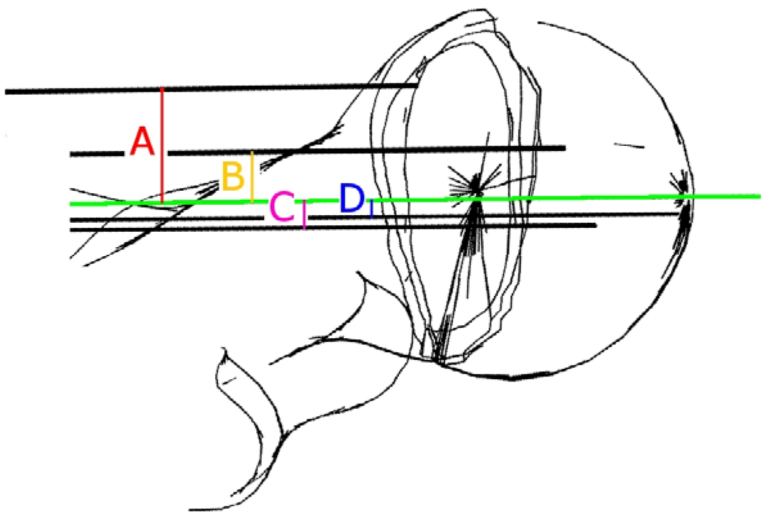


FIGURE G.2: Lateral view showing the distance of each mistake relative to the central axis (green line).

In addition this can be visualised if a view from the apex of the epiphysis is taken. This view is analogous to a graph drawn with the deviation for each mistake in the anterior direction on the abscissa and the deviation in the superior direction on the ordinate. This can be visualised in Figure G.3.

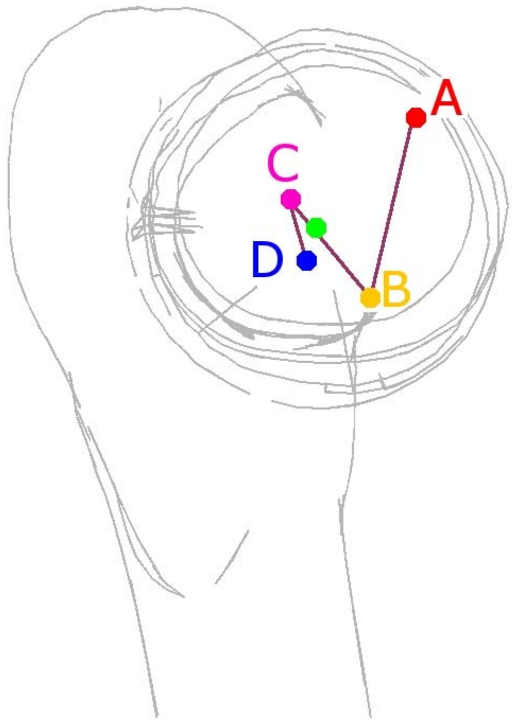


FIGURE G.3: A view from the apex, showing the error path for the 4 mistakes.

These quantities are then graphed to show how many errors are made, as well as how easily the trainees correct their mistakes in each plane.

A line-segment connecting these points is then drawn, and the total trajectory length calculated which gives an indication of how easily the trainee identified and corrected their mistakes.

Measuring each error with respect to the plane of the physis is valid, as the trainees are attempting to place the guide-wire with the entry-point in line with the centre on this anterior/superior graph, as well as attempting to have the trajectory orthogonal to this plane.

ETHICS APPROVAL

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UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE

24 February, 2004

MEMORANDUM TO:

Dr P Blyth

Anatomy with Radiology

Re: Application for Ethics Approval

The Committee met on 18 February, 2004 and considered the application for ethics approval for your research titled "Discerning skill levels using a virtual hip surgery simulator" (Our Ref. 2004 / 027).

Ethics approval was given for a period of three years conditional on: -

1. The Committee needs to receive a copy of the approval for this through the Research Office of Auckland District Health Board.
2. In the Participant Information Sheet, para 1 - replace "will be used as an educational tool for training" with "is being developed to assist training of ". Para 4 - At the end of line 1 add and will provide an indication of how other groups of opperators have performed but the names and individual results" deleting "In order - names". Note there is a typo after para 5. In para 6, delete "and will not be used commercially."
3. A Consent Form is not required as it is not anonymous.
4. Please clarify for the Committee the feedback mechanism.
5. Please forward the revised documents to the Committee as soon as possible for inclusion in the next agenda.

If the project changes significantly you are required to resubmit your appplication to the Committee for further consideration.

In order that an up-to-date record can be maintained, it would be appreciated if you could notify the Committee once your project is completed.

Please contact the Chairperson if you have any specific queries relating to your application. She and the members of the Committee would be most happy to discuss general matters relating to ethics provisions if you wish to do so.

Margaret Rotondo
Executive Secretary
University of Auckland Human Subjects Ethics Committee

c.c. Head of Department, Anatomy with Radiology

All communications with the committee regarding this application should indicate this reference number - (2004/027).

Appendix I

Multimedia

A CD-ROM is included with this thesis and contains a movie of the thesis and a series of 3 – Dimensional PDF documents. These interactive PDFs allow the three dimensional objects from the simulator to be viewed from all directions. To rotate around the scene, simply click and drag with the mouse. The PDFs are viewable with Adobe® Reader 7.0 or later. There is no additional installation of software required.

I.1 Bon*e*doc DHS Simulator example (simulator_example.mpg and simulator_example_sm.mov)

These movies (in two different formats) demonstrate a typical example of the simulator in use. An intertrochanteric fracture is reduced under image intensifier guidance, skin incision made, the guidewire introduced, adjusted until placed in a satisfactory position, and finally the definitive DHS screw and plate is placed. At the conclusion of the procedure, the position of the screw and plate is identified with a translucent femur, allowing identification of the 3 dimensional position of the implant, and the score-sheet from the procedure is shown.

I.2 Virtual Operating Theatre (theatre_view.pdf)

This PDF document depicts the 3-Dimensional view of the virtual operating theatre. Within the theatre the patient, traction table and image intensifier are visible. It is not possible to adjust the adjust the angulation of the traction table or image intensifier, nor are you able to view a virtual x-ray.

I.3 Completed operation (Fracture_DHS.pdf)

This PDF document illustrates a single DHS screw and plate, within a translucent femur.

I.4 Errors from Trainees (trainee_errors.pdf)

This PDF document shows all the misplaced guide-wires for the 4th year trainees operating on the Slipped Capital Femoral Epiphysis model. All the misplaced wires are shown, with graduations from red to yellow (first to last attempts). The threads of the screws are not shown for ease of viewing..

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