A virtual reality training tool for the arthroscopic treatment of knee disabilities

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ABSTRACT

Knee injuries are a common form of disability, but many can be treated using surgery. The minimally invasive approach of arthroscopy means faster recover times for the patient than when using open surgery, but the skills required by the surgeon are radically different. Although a number of arthroscopic training techniques are available all have problems either with cost, maintenance or availability. Through the medium of virtual reality, a computer based system can recreate the three dimensional geometry inside the knee, and allow the trainee surgeon to practice on it using replica instruments. In order to provide this facility at a feasible price, this paper describes work under way at Sheffield to develop a PC-based virtual reality arthroscopic training system. The resulting trainer has been tested by surgeons, and despite compromises made to accommodate the PC-platform, has been found to be extremely realistic at replicating some of the standard tasks of arthroscopy.

Keywords: surgery, training, arthroscopy, low-cost, PC

1. INTRODUCTION

Although extremely common, knee injuries can cause a great deal of distress and debilitation. In the case of professional sports people, an uncorrected knee injury can mean loss of livelihood for a time or the end to a career. In the case of ruptured ligaments, leading to knee instability, physiotherapy can often be employed to train the surrounding muscle structures to support the knee. However, for maximum recovery of knee performance, the damaged ligament must be reconstructed. In other cases, it may be necessary to surgically inspect the interior structures of the knee to ascertain the exact nature of the injury, and there will often be no alternative but to correct the fault by surgery.

Examination and repair of knee disabilities can be performed using open surgery. However, there are many benefits to using the minimally invasive approach of arthroscopy. In addition to the benefits to both patient and health care provider of significantly reduced recovery time (Banta, 1993), arthroscopic techniques minimise loss of synovial fluid and allow many of the knee structures to be examined in a relatively natural state. However, as with other ‘key-hole’ type operations arthroscopy can demand skills in excess of their open-surgery counterparts.

The arthroscope is a small metal tube containing a series of optics, creating a light source at the tip of the tube, and relaying the image from the tip of the tube back along optical fibres to a solid state camera, which then displays the image on a monitor. Although it is possible to get 0° arthroscopes where the viewpoint looks directly in front of the arthroscope, most use a view set at 30° or 70° off the axis. This allows the surgeon to be able to look around the immediate vicinity of the arthroscope tip simply by rotating the arthroscope around its own axis. Unlike open surgery where a large incision is made to provide a working area, the arthroscope is inserted through a small incision, usually just below the patella. Because the large incision in open surgery does not restrict the surgeon, he can manipulate the tools in a simple intuitive manner while directly observing the result. In arthroscopic surgery, however, any extra tools are inserted through a second small incision in a different location on the knee to the arthroscope insertion. The surgeon must navigate the tool blindly through the knee structures to the location of the procedure. The camera must also be navigated to the correct location. The arthroscopic surgeon will rarely be watching either the physical knee or his own hands, but instead must observe the operation on the view relayed to the monitor. Unlike the intuitive manipulation of

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open surgery, the ‘key-hole’ approach of arthroscopic surgery means that both tools and camera can only be manipulated by pivoting around the entry point while inserting further or withdrawing. The arthroscopic surgeon must therefore decipher a monitor image representing an arbitrary orientation pointing away from the direction of travel, navigate the tip of the rigid camera and tools through the labyrinth of structures in the knee, and perform the operation with two degrees of freedom less than in open surgery. Despite the complexity of the arthroscopic task, the procedure must be carried out with exact precision. It is easy to damage the sensitive components of the knee, and even slight scuffing of the articular surfaces will inevitably lead to arthritis in later life (Bamford, 1993). The learning curve for arthroscopic techniques is long, and to minimise the risk to real patients a number of training techniques are currently used to allow trainee surgeons to enter real surgery higher on the curve.

2. CURRENT TRAINING TECHNIQUES

Current training techniques for minimally invasive surgery encompass a number of different methods. For example triangulation, the ability to get both camera and tool to the same point from different entry points, can be learned by inserting the equipment through the side of a cardboard box. Simple procedures can also be initially practised using the same system, for example the skill of incision is often practised by peeling a grape within the box!

More realistic forms of training are afforded by the use of physical models and cadavers. Physical models recreate the main features of the anatomy of interest using synthetic materials. Simple physical models of the knee may not be much more than the tibia and femur held together by two bits of string representing the cruciate ligaments. Sophisticated physical knee models contain most of the ligaments and tendons available, the meniscii, patella, and surround them with artificial muscle and synthetic skin. Standard inspection and simple surgical procedures are practised on the physical models using a real arthroscope and tools. Although this allows familiarity with the standard operating equipment, it removes the equipment from use for real surgery, and also risks damage to the sensitive arthroscope in the early stages of training. In addition, physical models rarely replicate real anatomy or tissue properties. The models can be fragile in use and any damage to the internal components, whether accidental, or intentional as part of a practised procedure, requires that the model be disassembled, the damaged parts replaced and the model rebuilt. The constant need for repair and maintenance means that the use of physical models can be both expensive and time consuming.

Although cadavers provide a real joint to practice in, the internal structures can be significantly changed by the effects of death and preservation. Additionally, cadavers of healthy individuals are hard to come by, so most cadavers represent only a small percentile of the population. Cadavers are expensive to keep and the strict rules regarding their care makes their use for regular training troublesome.

One of the most successful methods for training surgeons in arthroscopic procedures is the use of live animals, usually pigs. However, various concerns about the welfare of animals in such training means that this technique is outlawed in the UK.

Since virtual reality allows the recreation of the three dimensional geometry of anatomy, and computer simulation techniques can be employed to model the dynamics within the body, it seems reasonable that a VR surgical trainer could provide a viable alternative to some of the existing training techniques.

3. VIRTUAL REALITY SURGICAL TRAINER

3.1 Current Surgical Simulators

Virtual reality trainers for traditional open surgery would rely on the trainee wearing instrumented gloves and a stereoscopic head mounted display. Apart from the problem of encumberment, head mounted display technology is not sufficiently advanced to produce an image of adequate clarity over a wide enough field of view to reproduce the normal working conditions of the surgeon. However, minimally invasive surgery displays the view of the operation directly onto a monitor, and is therefore is ideal for replication using desktop VR which replaces the video monitor with a computer monitor. Unlike open surgery, where the instruments may be manipulated over a substantial working area, minimally invasive surgery uses instruments inserted through a small incision, making computerised measurements and feedback on the instruments easier. Preliminary work has been carried out at a number of sites (Hon 1992; Coleman 1994) reproducing laparoscopic surgery. The virtual environment arises from monitoring the position of the laparoscope and other instruments in an artificial abdomen, displaying the appearance of the internal organs from the viewpoint of the laparoscope, and simulating the interaction of the surgical instruments with the internal organs, including the effect of gravity, blood flow etc. Despite the vast amounts of computer power lavished on these simulations, none can so far manage to include the complex particle flow models of blood release from incisions, and most surgeons find the dynamics of the internal organs vastly unrealistic.

Arthroscopic surgery has all of the problems of laparoscopic surgery but also has one other major complication - in addition to manipulation of the camera and instruments, a key part of arthroscopic surgery is manipulation of the limb itself. This movement is necessary to open up the joint for observation and so the eye/hand co-ordination required for minimally invasive surgery is compounded by additional proprioceptive and visual cues. This aspect does not yet appear to be addressed by other virtual reality arthroscopic simulators being developed (Logan, 1995; Ziegler, 1995) despite their use of high powered graphics workstations.

3.2 Arthroscopic Knee Surgery

The knee is one of the most complex joints in the human body. The two surfaces of the femoral condyles rotate and possibly slide on the surfaces of the tibial plateau, while the patella moves along the femoral groove. The ligaments limit the movement of the bones relative to each other, with four ligaments having specific restraining functions: the anterior cruciate ligament resists anterior subluxation of the tibia; the posterior cruciate ligament resists posterior subluxation; the medial collateral ligament resists abduction; and the lateral collateral ligament resists adduction, see figure 1. In addition to these limitations, the tibial-femoral interface is such that in full extension, the femur effectively locks into place on the tibia, after internal rotation of the tibia relative to the femur.

A standard inspection inserts the arthroscope slightly above the anterior horn of the lateral meniscus and close to the patellar tendon. The camera is passed up the intercondyle notch and examination starts at the apex of the suprapatellar pouch. The surface of the patella can be inspected by rotating the camera and withdrawing it slightly. Next the medial compartment is entered by turning the telescope downwards and flexing the knee. To examine the edge of the medial meniscus a lateral force must be applied to the patient's ankle with the knee in about 30° of flexion. This then also allows the camera to enter the lateral compartment and further inspection of the articular surface of the lateral condyle is achieved by both extending and flexing the knee. The postero-medial compartment can also be examined after flexing the knee to approximately 30°.

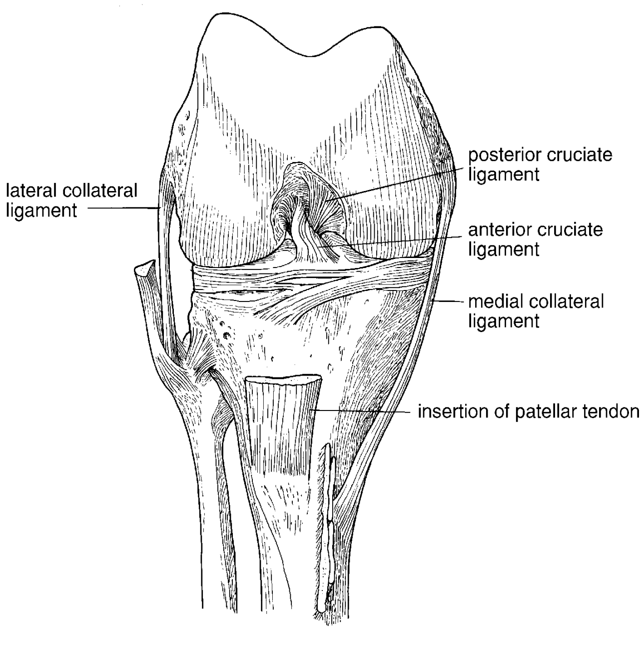


Figure 1. *The ligaments of the knee*

3.3 Arthroscopic Simulator Requirements

Eventually a fully functionally simulator is planned, able to represent many pathologies and patient types, and permitting the practise of diverse surgical procedures. However, initially the simulator must simply allow the trainee surgeon to perform a standard inspection similar to that summarised in section 3.2. Although fairly simple, a standard inspection requires that the trainee be able to recognise the major landmarks in the knee, triangulate both the arthroscope and a probe, and be able to move both around the compartments of the knee without damaging either the arthroscope or the knee itself.

If the resulting trainer is to stand any chance of being adopted as a commercial product, it must be priced at a level which would make it competitive with similar training technologies. The dynamic nature of the virtual environment in the arthroscopic trainer would normally require the use of high powered graphics supercomputers. However, to deliver the system at a competitive price point requires the use of a PC platform. The use of a PC is not as restrictive as it may first appear. The high-end Pentium PCs currently available have computational power at least equal to the lower cost graphics workstations, and there are an increasingly large variety of after-market graphics accelerators becoming available which deliver high-end workstation performance at a fraction of the price. However, careful design is still required to produce a convincing experience with the minimum of hardware. For this reason the approach taken is that the simulation need only *appear* to be correct as opposed to the high level of accuracy found in numerical models, which would be visually redundant.

Regardless of how complex the simulation of the environment may be, the effect would be completely lost if the trainee surgeon had to operate it in a different way to real surgery. Since all arthroscopic knee surgery inevitably requires the manipulation of the leg, a physical leg replica must be part of the system, although this need not be as complex as the physical models mentioned earlier, because all the internal components are modelled with the computer. Similarly, although only a synthetic arthroscope and tools are required in the simulator, they must represent their physical counterparts as much as possible.

Although the use of force-feedback is desirable in some other surgical simulators, the orthopaedic surgeons consulted did not think that it was significant for inclusion in the arthroscopic simulator. The leverage action of the tools around their entry points mean that, on the whole, only large forces would be felt by the surgeon. Given the sensitive nature of the knee's components, any action resulting in a force large enough to be felt would mean that the trainee had already made a mistake and a simple audio or visual cue would be sufficient feedback. However, the general feeling of the environment was thought to be important. Instruments should be weighted similarly to the real items, the artificial leg should be of the same heaviness, and the general damping action of moving the arthroscope and tools in muscle and other surrounding structures should be replicated.

The use of a computer as a mediator for the simulation means that extra facilities are available in excess of what would be with current training systems. Ideally the arthroscopic trainer could record the trainee's progress, provide multi-media tutorials and perhaps even automatic appraisal of the trainee's progress.

The virtual reality arthroscopic trainer currently being developed at Sheffield meets most of the above objectives. The following two sections describe the hardware and software components of the simulator.

4. SYSTEM HARDWARE

Because most of the features of the simulator are obtained using software, the amount of hardware has been reduced to a minimum. On the current system, the host computer is a standard entry-level Pentium equipped with 16Mb RAM and sound card. The graphics Matrox Millennium graphics accelerator card used is extremely low-cost, being intended primarily for computer games and multimedia, but nevertheless highly effective.

To create at least the same sense of realism as current training methods, an artificial leg and replica instruments are used. These allow the trainee surgeons to work into same way with the computer based trainer (figure 3) as they would with current physical models (figure 2).

Figure 2. *Physical model trainer* **Figure 3.** *Virtual reality trainer*

4.1 Artificial Instruments and Tracking

In order to allow the computer to track the position of the arthroscope and tools, these are fitted with receivers for the Polhemus Fasttrak electromagnetic tracking system. Although other tracking technologies are available, none were particularly suited for the task. Linkage based electromechanical trackers do not easily allow the use of replica instruments, and the connecting linkages can be obstructed by other parts of the system, and can also obstruct the surgeon in his task. There are some very good miniature 4 degree of freedom electromechanical trackers which are ideal for positioning over an entry point and tracking any instruments inserted, however the size and cost makes them inappropriate for use on the many possible entry points around the knee. Most other tracking technologies only measure orientation and not position, or require a constant line of site between the transmitter and receiver. The electromagnetic tracking system used does not require a clear line of site and is accurate to 0.03” RMS in measuring position and 0.15° RMS in measuring orientation. Because the instruments themselves are tracked, no obstructive hardware needs to be fitted to the artificial leg and multiple entry points can be easily accommodated. The small size of the receivers, about the size of the die, means that they can be easily mounted to artificial instruments. The disadvantage of using electromagnetic tracking is that the accuracy of the results can be adversely effected by the nearby presence of ferrous metals, or other magnetic fields. Even in ideal conditions, accuracy becomes worse if the receivers are further than 30 inches away from the transmitter. To minimise the effects of any environmental interference the transmitter unit is mounted inside the upper part of the artificial leg, just above the knee. Considerations of symmetry in the tracking mathematics means that at any time a receiver could be in either of two locations, and therefore a hemisphere of operation is declared for the tracker. Although the transmitter must be close to the knee for maximum accuracy, its position has to be carefully fixed to minimise the occurrences of an instrument being used behind it and generating an erroneous result.

The need to minimise ferrous metal in the environment also means that simple plastic replicas of the arthroscope and tools are used. Currently, the tools still need to be artificially weighted to a level similar to the real tools, but the shapes are identical to their real counterparts. This is especially important in the case of the arthroscope, where certain features of the tool, such as the insertion lug for the light source, are used by the surgeon to determine the roll orientation of the end optics. In addition to replacing the redundant real items, the plastic replica of the arthroscope and tools are cheap enough to be disposable in the event of breakage by unskilled handling, unlike their real counterparts.

4.2 Artificial Leg

The artificial leg is different from the physical models currently used in training, in that it has effectively no internal components. A simple leg shell can be used since all of the structures inside the knee are modelled within the computer. However arthroscopic surgery inevitable requires the manipulation of the lower leg to open up the various compartments of the knee for access and inspection. Although a real knee can be made to rotate and translate in a number of planes, the two key movements are flexion (bending forwards and backwards) and abduction (side-to-side). The amount of abduction available is dependant upon the degree of flexion, with no abduction possible at full extension. This movement is modelled in the artificial leg by having small cams on the flexion joint lock the joint in full extension, but permit increased abduction-adduction with increased flexion. To simplify design, the abduction-adduction is around a single axis in the centre of the joint, unlike the real case of rotating around the left or right femural condyl depending on current displacement. Additionally, flexion is physically modelled as a pure rotation, as opposed to the combination of rotation and translation in a real knee, The difference in the feel of the manipulation with this simplified mechanism is not thought to be a significant factor in operational reconstruction. The artificial leg can be easily weighted by using plaster of Paris in the lower, and the upper leg is clamped to a table, in a similar way to the surgeon strapping the real upper leg, or wedging it against a stop. With the current prototype, figure 4, there have been problems with the internal hinging components occasional obstructing the movement of the instruments within the knee cavity. Another prototype is currently under design with a redesigned mechanism to minimise obstruction, and also to include a thick synthetic skin, to provide the damping action of the muscle structures, and provide a more realistic entry point than the simple hole in an extension of the lower leg currently used.

Figure 4. *The artificial leg, showing hinge mechanism and entry point*

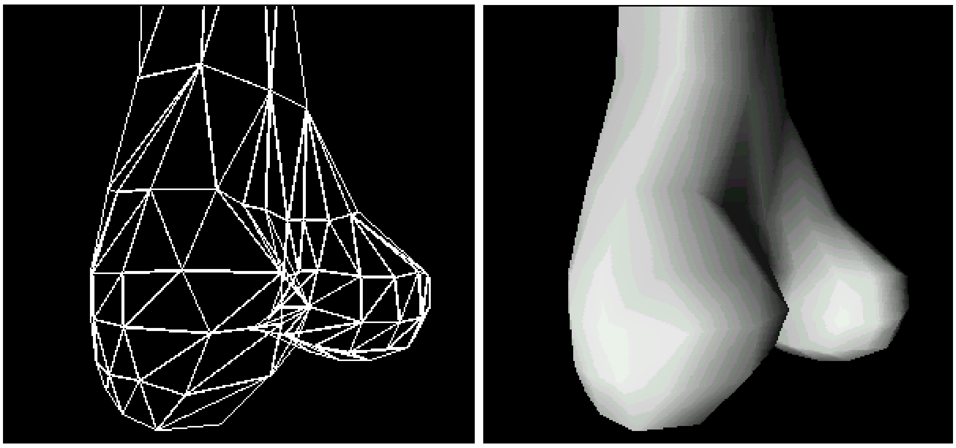
Currently, a third electromagnetic receiver is used on the lower leg to monitor flexion and abduction. However, since the leg can only be moved in two degrees of freedom, each of which could potentially be monitored using simple electromechanical trackers on the hinges, this system is liable to change in the near future. Although this adds another component to the hardware of the system, it also allows the use of a lower cost electromagnetic tracking system for the arthroscope and tool.

5. SYSTEM SOFTWARE

The VR toolkit used as the basis of the simulation is the Visual C++ based WorldToolkit from Sense8, running under Windows NT. The toolkit provides functions for most of the high level tasks of handling the peripheral devices, manipulating objects, detecting collisions etc. in addition to allowing access to lower level facilities of OpenGL.

5.1 Graphical Objects

The geometry of the knee components featured in the trainer were obtained by digitising plastic replicas using the 3Draw from Polhemus. Although this required the writing of digitising software for the product, it was thought the optimum route. Commercial data sets are available but tend to be expensive and overly detailed. Conversion of volumetric data from MRI and CT scans to surface data is also problematic, often produces inexact images, and is surrounded by difficulties caused by medical ethics considerations. Digitisation of the replicas by hand allowed customisation of the digital object, including having the edges of the polygons follow key contours on the real objects, and having increased polygon density around the main area of interest, the articular surfaces. It is essential to only have the minimum of polygons necessary to provide a sufficient representation of the object. Higher polygon counts mean slower rendering rates on the screen, can cause transformation delays when the objects are moved, and cause similar penalties when other polygon specific functions are used, e.g. texture mapping, smooth shading, collision detection etc. Although the model used has only a few hundred polygons in each object (figure 5a), the use of smooth shading makes the object look much more detailed (figure 5b). The low resolution of the data set is only revealed when looking at the object profile, and this is not thought to cause significant problems, although there may be a risk of trainee surgeons learning to use the discontinuities of the profile as landmarks, instead of the structures themselves.



a) Wireframe *b) Smooth shaded*

Figure 5. *Graphical object display*

5.2 Kinematic Simulation

The initial model of knee movement developed was an extension of the four bar link model used by O'Connor and Zavatsky (1993). This only models the two dimensional flexion-extension movement of the knee. The four links in the model are the two cruciate ligaments, assumed to always be under tension, and their two pairs of connection points, see figure 6. The two cruciate ligaments actually provide the limits to the flexion-extension movement of the knee, with the posterior cruciate ligament under maximum tension at full flexion, and the anterior cruciate ligament under maximum tension when the leg is straight. This model has been extended to provide a similar action to O'Connor and Zavatsky's model but with the cruciate ligaments undergoing changes in tension, and to provide the flexion dependant abduction-adduction limiting effects of the collateral ligaments (Hollands, 1995).

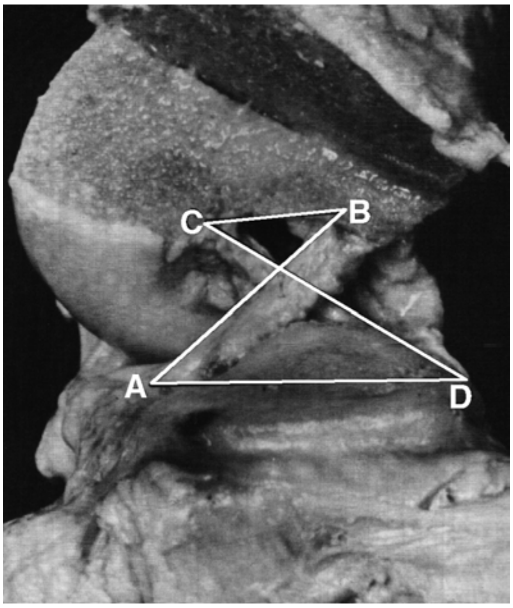


Figure 6. *Four bar link structure of the cruciate ligaments*

When the training system was being initially developed, the computing platform used then was unable to perform complex transformations at an acceptable rate, so for reasons of necessity the four bar link flexion movement was converted to a simple rotation around a point in the femural condyles. It was found by experimentation that a similar translation and rotation movement to the bar link model could be obtained by rotating around a point offset behind and above the centre of the femoral condyl. In the current model, the offset rotation has been retained, but the limiting action of the ligaments included, similar to those in the extended four bar link model.

Each cruciate and collateral ligament has fixed connection points on the femur and tibia. After any relative movement of the bones, the distance between the two end-points of each ligament can be calculated to determine ligament tension and provided limitations of movement, as in the four bar link model. Since the collateral ligaments are not seen in normal arthroscopic surgery, only the cruciate ligaments are represented in the virtual joint. The ligaments must stretch and contract with joint manipulation, however the usual techniques for modelling deformable objects are numerically too intensive to keep a satisfactory update rate on the PC platform. Instead, a generic shape for each ligament is constructed and placed so that one end of the object coincides with its connection point on one of the articular surfaces. The ligament object is then rotated so that it lies along the vector linking the two connection points on each articular surface. The 'ligament' is then scaled by the amount necessary to cause the other free end to 'butt up' to its second connection point on the other bone surface. If the generic shape chosen is similar to a spiral, the scaling factor then causes the spiral to extend and contract in a manner which mimics the real ligament bundle.

Although the appearance of the objects within the display could be further enhanced with the use of more advanced shading techniques and extensive texture mapping, this would create an appearance far clearer than in real arthroscopic surgery, where the view is obscured both by the very narrow focal depth of the camera, and various bits of debris floating around in the saline solution being pumped though the joint. Figure 7 shows a snapshot from a real arthroscopic inspection, and figure 8 shows a comparative view from the virtual arthroscopic trainer. The use of attenuated light sources, scene fogging, visual noise and other techniques are currently under investigation in the Sheffield simulator to try to replicate the 'poor' image quality found in real systems.

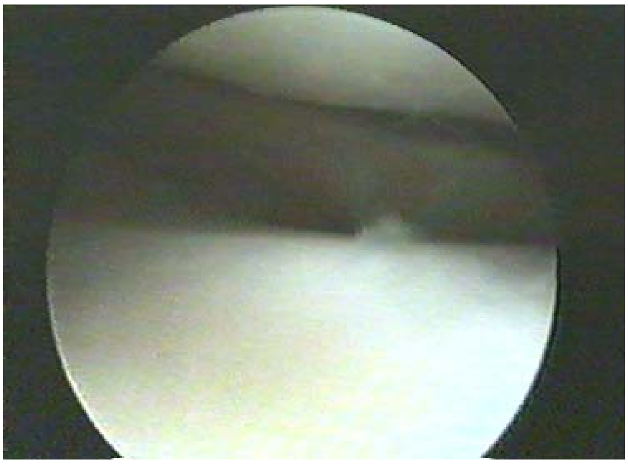


Figure 7. *Real arthroscopic view*

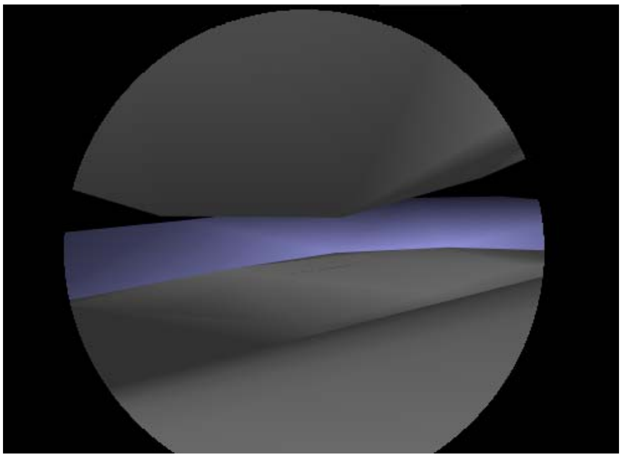


Figure 8. *View from virtual arthroscopy trainer*

5.3 Under Investigation

In addition to the visual effects mentioned in section 5.2, a number of other features are also currently being experimented with. Although the knee does not contain a great number of deformable objects, some of the key components of the knee have deformable characteristics which need to be modelled even in a simple inspection. Although a number of techniques are available to model deformable objects, all are relatively computer intensive and their inclusion in the PC-based model would slow it down by an unacceptable amount. In the same way as a simple solution was found to create the illusion of deforming the ligaments, investigations are under way to devise simple solutions to recreate the highly constrained deformations found in the other knee components.

Collision detection is an integral part of the trainer. Constant checks must be made to monitor the position of the instruments within the knee and any collision with the internal structures is indicated by aural and visual cues. However, even with the low polygon density of the graphical objects used in the trainer, the time required to detect collision using a polygon intersection technique is far too long. The simple bounding boxes used for collision detection in large scale systems are inappropriate in the knee model because the irregular surfaces of the objects combined with their close proximity would yield constant collision flags. Voxel based collision detection of non-deformable objects have been reported as being very efficient in other surgical simulators (Logan, 1996), and their suitability for inclusion in the PC-based trainer is currently being investigated.

5.4 The Display

Obviously, the key feature of the display is the simulated view through the arthroscope. However, a number of additional displays are also available, see figure 9. A second view onto the knee environment can be requested showing an overview of the entire knee for orientation purposes. Unlike the primary window, whose viewpoint position is determined by the position of the synthetic arthroscope, the viewpoint in the overview window is controlled by standard mouse. There are facilities available for the user to record a session, and then play it back at a later time, and

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the orientation window then provides valuable information about what was actually happening to the arthroscope to produce the pictures seen in the primary window. In addition to the user being able to play back their own sessions, expert sessions can be examined for comparison.

A third window can show captured images from inside a real knee. A previous project (Hollands, 1995) examined the feasibility of developing a trainer only using a large database of captured images. It was determined that a prohibitive amount of space was required to store all the images necessary for a pseudo-continuous simulator. However, the database developed is used in the current simulator to provide a view representative of the view in a real knee which would be seen at, or near, the position of the synthetic arthroscope. As the synthetic arthroscope is moved around inside the knee, the image database constantly updates the window with the picture taken at the location closest to that of the current viewpoint. The result is a discontinuous, but photorealistic, arthroscopic simulation in synchronisation with the continuous virtual simulation.

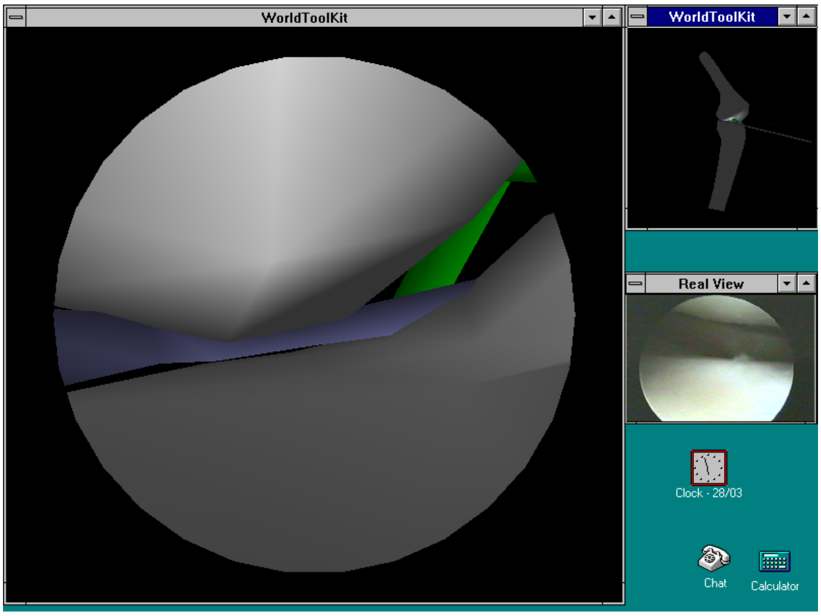

Figure 9. *Virtual arthroscopy trainer display*

6. CONCLUSIONS

Knee injuries are an exceedingly common form of disability, and in those requiring great mobility the consequences can be severe. Many knee disabilities can be fixed by corrective surgery and arthroscopy offers an approach with minimum intrusion and fast recovery times. The skills required for arthroscopic surgery are radically different from those for open surgery and a virtual reality trainer could provide a cheap, effective alternative to current training techniques. Its closest counterpart in traditional training techniques is the physical model which can be expensive to maintain since it must be disassembled and damaged parts replaced after any surgical procedure has been practised. In the virtual counterpart, the joint anatomy can be 'repaired' simply by resetting the software. Since the virtual arthroscopic trainer only uses low-cost plastic replicas of the arthroscope and instruments, it has also been identified by training centres as a lower risk method of training than using the physical model. Newly qualified surgeons often damage the expensive real surgical instruments through inexperience when using the physical models.

We believe that the combination of virtual reality and simulation allows the creation of an extremely flexible and useful training tool for surgery. However, we also believe that any such tools must be created in a manner as to be economically feasible, or they will stand no chance of being incorporated into standard training programmes.

The prototype system described here has been used by a number of surgeons from the Royal Hallamshire Hospital and Northern General Hospital in Sheffield and all have been impressed by the sense of realism afforded by the necessity for correct hand-eye co-ordination when manipulating the dummy instruments together with the leg model within the virtual environment. Development of the virtual training system is fully supported by Smith and Nephew Surgical who have expressed an interest in incorporating the final trainer in their arthroscopic courses and training centres throughout the country.

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