Human Factors Related to a Virtual Reality Surgical Simulator: The Sheffield Knee Arthroscopic Training System

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Arthroscopy of the knee joint is a common surgical procedure. However, although this minimally invasive technique offers advantages to patients and to health care providers, it places additional demands upon the surgeon, requiring enhanced psychomotor skills and manual dexterity. Current training methods do not prepare surgeons adequately before practice on patients occurs, thereby placing patients at potential risk of injury. This paper outlines the human factor requirements for a Virtual Reality based surgical simulator and describes the advances made to the Sheffield Knee Arthroscopy Training System in the light of feedback from surgeons. Initial work to produce finite element models of the medial and lateral menisci of the knee is described and images of deformations of the menisci are displayed. The training system has been well received by the surgeons and represents a new and potentially more challenging alternative to current arthroscopic training methods.

Keywords: virtual reality, arthroscopic training, human factors, deformation

1. Overview of Arthroscopy

Arthroscopy is a form of endoscopy or minimally invasive surgery that is concerned specifically with joints. Arthroscopy offers advantages over traditional open surgery, to patient and healthcare provider alike, in that procedures are generally less invasive, resulting in smaller wounds, increased rates of recovery, reductions in hospitalisation episodes and therefore, reductions in patient intervention costs (Banta, 1993).

While these advantages are attractive to the healthcare provider, there are related disadvantages. Arthroscopic equipment is expensive and surgeons require additional training to acquire the competence to operate efficiently and safely. Surgeons agree that current initial training protocols are insufficiently challenging of technique and consequently surgeons are entering the operating theatre with inadequate skills to use arthroscopic technique to its best advantage. Thus, patients are being placed at risk from inexperienced surgeons. The time taken to gain proficiency is estimated at between three months and two years, dependent on the number of hours spent on practice (Dumay and Jense, 1995).

The most complex joint within the human body is the knee joint and it is one of the most frequently injured joints, necessitating surgical intervention that in recent years is usually performed by arthroscopic means. In England alone during 1994/5, 28,530 primary arthroscopic procedures were conducted. These figures were provided by the NHS Executive and do not include the private sector or follow-up procedures. Examples of the risks to patients incurred include: injury from inadvertent contact with articular surfaces, inappropriate placement of graft cruciate ligaments and missed surgical features such as meniscal debris, causing additional, unnecessary and costly surgical procedures.

An arthroscope is used to provide the view of the inside of the joint. It is a rigid instrument comprising fibre optics and a CCD camera that relays the joint image to a video monitor. The arthroscope and the instruments required to perform surgical procedures are introduced into the joint via small skin incisions. Thus, the usual six degrees of freedom are restricted to only four because translations in the X and Y directions are constrained by the skin and soft tissues around the incisions.

This paper identifies human factors associated with the training of arthroscopic knee surgeons. It describes the progress in the development of a VR training system, detailed by Hollands and Trowbridge (1996a and 1996b), the Sheffield Knee Arthroscopy Training System and discusses how these human factor requirements have been incorporated into the system. The final section of the paper describes initial efforts to incorporate soft tissue deformation into the training simulator.

2. Sheffield Knee Arthroscopic Training System (SKATS)

To help overcome the limitations associated with current arthroscopic training, an arthroscopic training system that uses Virtual Reality techniques is being developed and refined.

2.1 P.C. based system

It has been designed to run on a P.C. platform because an important requirement for a training system is that it should be cost effective. Ideally, each district general hospital that provides arthroscopic surgery should have its own arthroscopic training system, in addition to those that should be possessed by specialist surgical skills' workshops. Not only must the hardware costs be considered but the maintenance costs of the system must also be taken into account. Other VR based arthroscopic systems have been created (Logan, 1995; Ziegler et al., 1995; Mabrey and Merril, 1996) but these use high-end graphics workstations as their delivery platform and therefore, because of their cost, are less likely to be accessible to district general hospitals.

The system comprises an Intergraph TDZ 310 Pentium Pro 200MHz with 64 Mb of RAM, a Polhemus FASTRAK electromagnetic tracking system together with a tracked replica limb, arthroscope and instruments. The prior version of SKATS (Hollands, 1996) has been upgraded to allow for additional graphics capabilities.

2.2 Physical lower limb

An integral component of the system is the replica of the lower limb that allows the surgeon to interact with the surgical simulator in a natural and intuitive manner, that is, in a similar fashion as when operating on a human patient. Other surgical simulators, can be effective using a simple, hollow "black box" such as the laparoscopic systems described by Satava (1994). However, a fundamental component of arthroscopic surgery is the requirement to manipulate the patient's limb so a black box approach would not be acceptable to the end-user, the surgeon. Other arthroscopic simulators (Logan, 1995, 1996; Ziegler and Müller, 1996, 1997) also include a replica knee, however it is not described whether these knees are capable of being manipulated in a realistic manner.

The Sheffield Knee Arthroscopy Training System in use, showing the replica knee

joint

2.3. System software

The software used to create the simulation is the Visual C++ based WorldToolKit (WTK) from Sense8, running under Windows NT.

3. Clinical Feedback

The SKATS system has been demonstrated at the East Berkshire Anterior Cruciate Ligament Symposium, November 1996 and at Ortho '96, October 1996, Sheffield. These forums provided ideal opportunities to gain important feedback from both experienced (greater than ten year's practice) and trainee (up to 1 year's practice) arthroscopic surgeons. Surgeons were invited to practice on SKATS and were encouraged to give feedback on the system and general requirements for arthroscopic training via interview and questionnaire.

3.1 Physical limb

The training system utilises a physical model of the lower limb as input to the graphics renderer. The leg is jointed such that surgeons can manipulate the knee joint realistically. The replica limb includes the capability for the surgeon to be able to flex and extend the knee together with the flexion-dependent movements of abduction and adduction that are required to gain access to certain areas of the joint for improved visualisation. The surgeons found this form of interaction with the system intuitive and soon became engaged in the process of manipulating the replica limb to maximise the visualisation of the joint. Following these demonstrations, the limb model has been re-designed to allow easier access to the posterior surface of the physical patella model, an important feature in arthroscopic knee joint inspection.

3.2 Validity of system

It was interesting to note that the more experienced surgeons were able to orient themselves on the simulator more quickly than the less experienced surgeons, who required some guidance in the initial stage of practice. In addition, surgeons in theatre who tend to rotate the whole arthroscope rather than rotating solely the arthroscope optics - a less effective method of navigation likely to cause loss of orientation – also reproduced the same technique using the simulator. These observations have indicated some degree of face validity for the training system.

3.3 Haptic feedback

Many of the haptic feedback requirements discussed were directed at the physical components of the training system.

3.3.1 Physical components

The surgeons used to rotating the arthroscope optics commented that the degree of resistance to roll was insufficient. This has now been addressed by increasing the stiffness of the arthroscope model such that the optic roll feels more realistic to the surgeons.

Using 6mm-neoprene material on the anterior surface of the limb model has simulated the feel of the skin. This has been an important consideration for the resistance at the entry incisions or portals, where the arthroscope and surgical instruments are inserted. The material used in the previous design did not provide sufficiently realistic resistance to the manipulations of the arthroscope and instruments. Surgeons felt that there was still some room for improvements to this resistance but that it was adequate for training purposes.

The decision making process involved in placing the entry incisions or portals was identified by the surgeons as an important feature of initial arthroscopic training. Because the neoprene material can cheaply and easily be replaced for use by another trainee, a surgeon can be afforded the opportunity to select and create his/her own portals. Immediate feedback regarding the suitability of the portal placement is available to the trainee via the graphics display.

3.3.2 Force feedback

Currently there is no force feedback incorporated into the simulator. The surgeons gave conflicting views as to the requirement for force feedback. The trainee surgeons stated their belief that it was a vital source of information, particularly for navigation. In contrast, the experienced surgeons felt that it would enhance the learning process if trainees did not become reliant on force feedback, especially if the contact came from the easily damaged articular surfaces. Instead, it was believed that trainees should become more proficient at using the visual cues from the monitor to navigate around the joint. In this respect the lack of force feedback was seen as a potential benefit. However, for more advanced joint inspection, for example testing the integrity of cruciate ligaments, some kind of haptic feedback was seen as necessary.

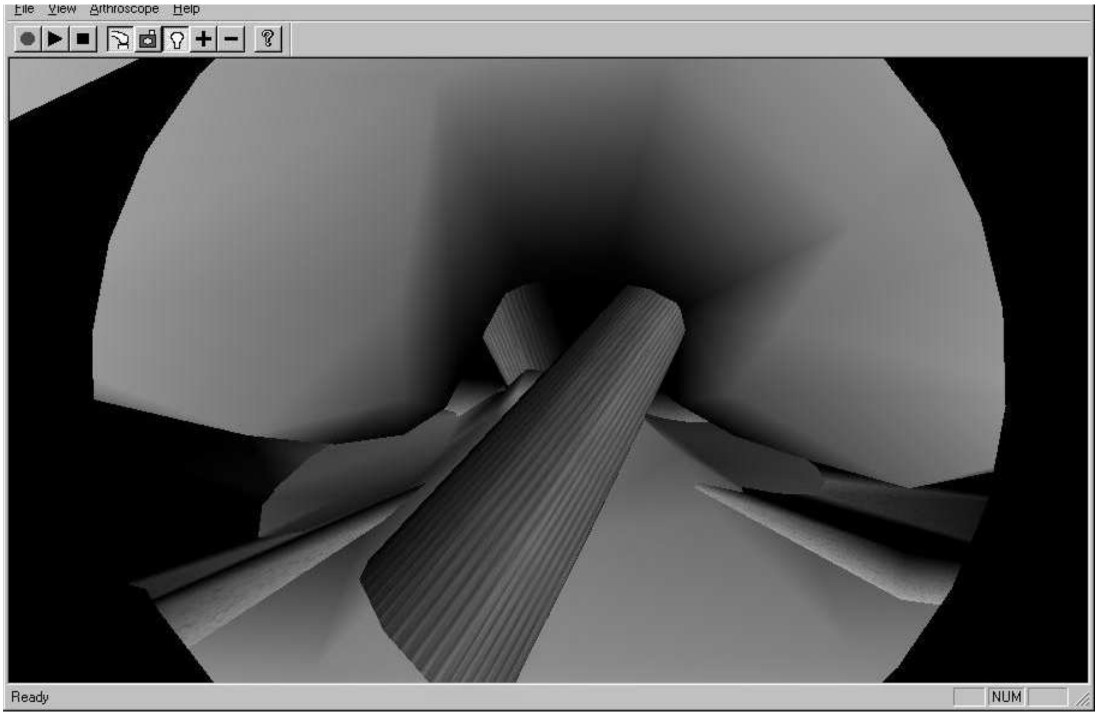
3.4 Collision Detection

The surgeons found the simulator to be challenging of technique. This observation addresses one of the major complaints against the current method of using replica knees for training. The replicas allow too much space within the joint making navigation easier than in a real knee, and thus giving the trainee surgeon a false sense of competence. Voxel-based collision detection has been incorporated into the simulator for the bony surfaces. Visual and audio cues are provided to the trainee when contact with any articular surface is made. The experienced surgeons were seen to have fewer collisions than the trainee surgeons.

3.5 System performance and realism

The performance of the system has been optimised by minimising the total number of polygons used to create each geometry model whilst the appearance of the geometry models has been optimised by the use of smooth shading. To improve the appearance of the anatomical detail of the soft tissues, texture mapping has been applied. A suitable texture map has represented the fibre structure of the cruciate ligaments and the menisci appear more life-like due to the application of texture.

Surgeons were content with the update rate and commented that it was more important to them to have minimal lag with realistic dynamics than to have photo realistic graphics. Ultimately though, a VR surgical simulator should aim to achieve both.

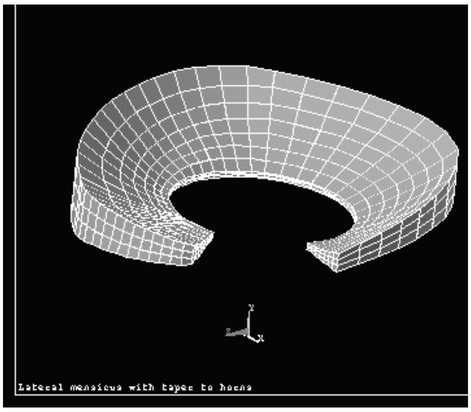


An example screenshot from the Sheffield Knee Arthroscopy Training System. (The texturing of the anterior cruciate ligament can be seen as the brown cylindrical feature in the centre).

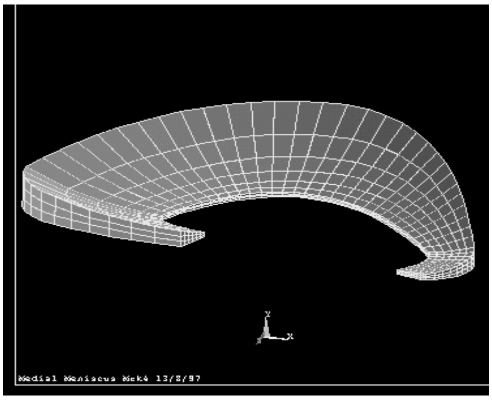
4. Current Developments

The response from the surgeons has been extremely positive. The authors believe that the training system already provides an improved training environment compared with current physical training models such as the Hillway knee. This view is shared by the designer of the Hillway Knee, a highly experienced surgeon who, after using the system, stated that the VR simulator represented the way forward for future training of arthroscopic knee surgeons. However, to increase the functionality and the degree of interaction available to the user, the simulation must provide appropriate soft tissue deformations. Examples of the deformations cited by the surgeons included: lifting and probing the menisci to check for meniscal tears, hooking a probe over the outer rim of the menisci to check for integrity of the coronary ligament and hooking behind the cruciate ligaments to test for ligament integrity.

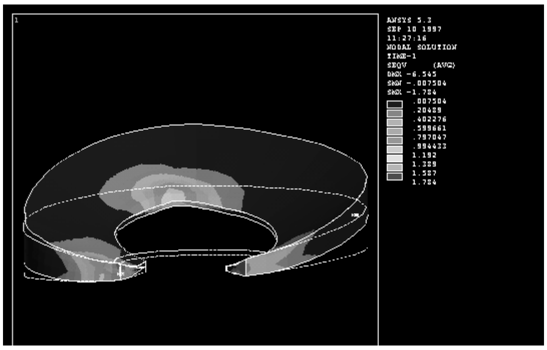
Because the current version of the training system does not provide for soft tissue deformations, work is underway to address this lack of interaction. The menisci have been modelled using finite element (F.E.) modelling (ANSYS 5.3, Swanson Analysis Systems). Three-dimensional finite element models of the medial and lateral menisci have been built and analyses of the deformations involved in lifting the menisci have been performed.



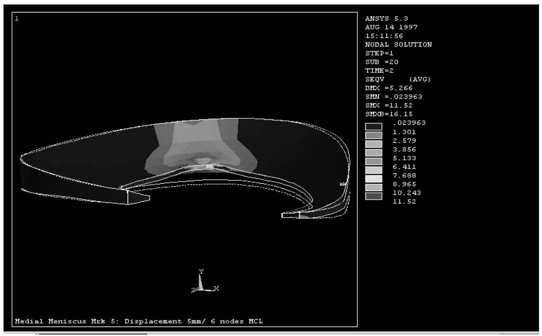
Lateral Meniscal F.E. mesh



Medial Meniscal F.E. mesh



Lateral meniscus post 5mm lift
(initial position: white outline)



Medial meniscus post 5mm lift
(initial position: white outline)

Isotropic linear elastic material properties have been used to model the menisci while the elements used to create the 3D F.E. mesh were solid 8 node brick elements. Animations of the deformations incurred by the menisci undergoing a lift have been created. Displacements were applied in the Y direction at combinations of nodes selected to mimic contact by an instrument probe. These meniscal lift deformations have been viewed by experienced arthroscopic surgeons who are happy with the validity of the appearance of the deformations. A database of the nodal co-ordinates of the displacements is being created and the ANSYS nodal data is being converted to a format suitable for inclusion within WTK.

Voxel-based collision detection (Hollands, 1996; Logan, 1996) has been used to detect collisions with the non-deformable bony surfaces within the simulator. Because a voxel map for a deformable model would have to be recalculated after each deformation, it may not be suitable for use with the deformable menisci. Polygon intersection collision detection (using a low polygon count model) will be investigated in addition to voxel-based collision detection to select the most suitable (in terms of speed) method of triggering a meniscal deformation.

Two approaches to integrating the deformations into the WTK-based simulator are being explored. The first is to create a database of co-ordinates with a model-related index system to permit rapid display. The second is an algorithmic approach (based on the F.E. data) which would allow a systematic real-time display.

5. Conclusions

The development of the Sheffield Knee Arthroscopy Training System has been assessed by both experienced and trainee surgeons. The feedback from the surgeons has been extremely positive, with a recommendation that SKATS could already fulfil the initial training needs of arthroscopic surgeons. Work is in progress to achieve some of the additional necessary requirements identified by the surgeons, such as increased interaction in the form of soft tissue deformations. A finite element analysis approach is being taken to solve the problem of soft tissue deformation. Initial work is concentrating on meniscal deformation although other soft tissues, such as the synovial joint capsule will be modelled in the future.

Smith and Nephew Healthcare Ltd have expressed interest in incorporating the final training system into their arthroscopic skills' workshops and training courses throughout the country.

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