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The Feasibility of a Mixed Reality Surgical Training Environment

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Abstract: The Sheffield Knee Arthroscopy Training System (SKATS) was originally a visual-based virtual environment without haptic feedback, but has been further developed as a mixed reality training environment through the use of tactile augmentation (or passive haptics). The design of the new system is outlined and then tested. In the first experiment described, the effect of tactile augmentation on performance is considered by comparing novice performance using the original and mixed reality system. In the second experiment the mixed reality system is assessed in terms of construct validity by comparing the performance of users with differing levels of surgical expertise. The results are discussed in terms of the validity of a mixed reality environment for training knee arthroscopy.

Key words: *Tactile augmentation, passive haptics, surgical simulator, training, and arthroscopy*

1. INTRODUCTION

This paper describes research and development on the Sheffield Knee Arthroscopy Training System (SKATS), a virtual environment for training arthroscopic (keyhole surgery of the joint) skills. Here we describe the development of the system from a visual-based virtual environment, to a mixed reality system incorporating tactile augmentation. The motivation for this design approach is described as well as two experimental studies used in the initial evaluation of the system.

1.1 The Sheffield Knee Arthroscopy Training System

SKATS is a PC based simulator offering a cost effective and safe means of training basic arthroscopy skills [1]. Knee arthroscopy involves the surgeon working with a pair of instruments, an arthroscope (camera) for viewing the joint, and a probe, for exploring structures. The condition of the knee is determined through manipulation of the patient's limb and navigation of the surgical instruments to examine the knee surface. Effective performance is dependent on visual, haptic and proprioceptive (awareness of own position and motion) information [2]. SKATS is aimed at familiarizing trainees with the knee environment prior to patient-based practice and training basic skills such as navigation and orientation within the 3D space, and triangulation of the surgical instruments.

1.2 Rationale for Mixed Reality

Tactile augmentation has been considered as a means of providing physical contact within the SKATS environment due to the documented challenges of incorporating an existing commercial or an innovative, bespoke haptic device [3][4][5][6][7][8]. The demands of this specific application are not inconsequential. During knee arthroscopy the surgeon uses haptic cues for a range of tasks, from guiding navigation, to the identification of tissue properties for diagnostic purposes. Arthroscopy is a bimanual task for which full haptic simulation would require two, four degree-of-freedom devices to apply reactionary forces in response to contact with a variety of knee structures and ideally fit within a fully manipulable physical limb model. These user requirements present substantial technical challenges to achieve high-end fidelity [9][10]. However, following extensive analysis of task performance and user requirements capture, it was concluded that a complex simulator, with total physical and functional fidelity is unnecessary for basic skill acquisition [10][11]. Instead it is argued that the requirements can be met using tactile augmentation [2].

1.3 Tactile Augmentation of SKATS

The original SKATS system was comprised of a hollow plastic model of the limb, replica surgical instruments and a monitor displaying the virtual internal view of the knee joint (see Figure 1). A 3D computer-generated environment provided a real-time, interactive simulation of the tissue. The visual model responds to the user's actions as the location and orientation of the physical leg and the arthroscope and probe are tracked. Movement of the leg and tools therefore resulted in a corresponding change in the virtual image (see Figure 2).

Evaluation of the original system by orthopaedic surgeons pointed to user acceptance issues due to the absence of structural contact, the lack of physical resistance to guide navigation, and the capacity to pass through apparently solid surfaces upon contact within the VE [1]. This is likely to affect skill acquisition and disrupt the level of immersion and the sense of presence within the VE [6][12][13][14][16]. Given these issues and the challenges associated with incorporating mechanical haptic feedback for this application tactile augmentation has been considered as a transitional solution.

Tactile augmentation (also called passive haptics [18][19]) involves the combination of a synthetic model within a virtual space to provide haptic cues [2][8][15][16]. As a form of mixed reality it is believed to improve the quality of a human-computer interface and enhance the sense of presence over a purely visual representation [15]. Research carried out by Insko [18] showed that augmenting a high fidelity visual VE with low fidelity objects, which they call 'passive haptics' can increase the sense of presence as measured by questionnaires and physiological responses. Experiments showed that navigation performance in the real world whilst blindfolded was more effectively trained by a VE incorporating passive haptics than a non-augmented VE. It has been applied in healthcare applications to treat phobias of height [20] and spiders [21] and to some extent in training simulators [22].

Potentially, it is a more efficient solution in terms of both time and cost, being technically more straightforward to develop and integrate into a virtual environment (VE) than a mechanically generated haptic device.

INSERT FIGURE 1 & 2 ABOUT HERE

Therefore subsequent development of SKATS has involved enhancing the system to provide a greater level of interactive realism. The bone and soft tissue virtual models have been redeveloped from high resolution volumetric magnetic resonance images of the knee. A more realistic, manipulable leg model containing internal solid models of the femur and tibia has also been developed. This forms a mixed reality environment where physical resistance is felt upon contact with the virtual bone. The solid bones have been generated from the SKATS virtual bone model using stereo-lithography. They are made of epoxy materials to give strength and durability, and have been coated with a simulated cartilage surface formed from silicon sheet (see Figure 3). In the following sections two experiments are described that investigate the viability of this mixed reality approach and look to address three main questions:

1. What effect does tactile augmentation have on performance?
2. Does the system allow differentiation of expert and novice surgical performance?
3. How do the users feel about the system?

2. EXPERIMENT 1: EVALUATION OF TACTILE AUGMENTATION

The first experiment was undertaken to determine the impact on novice task performance of the integrated bone and cartilage model. The experiment involved comparing performance on the tactile augmentation version of the system

(SKATS A), to that on a visuals only version (SKATS B). It was hypothesized that:
H1. Task performance would differ on SKATS A and SKATS B
H2. Performance would not readily transfer between SKATS A and SKATS B

2.1 Method

Participants

14 participants, 6 male and 8 female, with a mean age of 30 years (range 22-46) took part in the experiment. 12 were right-handed and 2 were left-hand dominant. None of the participants had any surgical expertise or previous experience using SKATS.

Equipment

Two versions of SKATS were used; they only differed in terms of the interior of the physical leg model. The software was written in Microsoft C++ (Microsoft, Redmond, WA) with some of the functions used for data handling and simulation making use of WorldToolKit (Release 9, Sense8, San Rafael, CA). The location and orientation of the physical leg, arthroscope and probe were tracked by the miniBIRD® electromagnetic tracking system (Ascension Technology Corporation, Burlington, VT [23]. The virtual image was presented to the participants on a 17 inch flat panel display.

The difference between the models lay in the haptic feedback offered. SKATS A included tactile augmentation through the inclusion of a physical tibia, fibia and cartilage surfaces within the leg model. The miniBIRD® system recorded the positions and orientations of sensors attached to the tibia, arthroscope and probe, relative to a transmitter mounted on the femur. The leg model was designed to allow fine tuning of the position of the bones and their relative movement; a calibration routine was established to ensure alignment between the physical and virtual knees. In contrast, SKATS B incorporated a hollow leg model therefore providing no touch feedback on contact with the virtual joint surfaces.

Procedure

A standardized experimental protocol was used. As the participants had no experience of arthroscopy, training was given regarding the anatomy of the knee, and how the tools and leg could be manipulated to view the joint space. The system was demonstrated and the participants had a few minutes to familiarize themselves with the virtual environment and the instruments.

The participants were randomly allocated to one of two groups. Group 1 completed training and the experimental task on SKATS A first; group 2 used SKATS B. The training task involved navigating the knee area to find the numbers 0 to 7 which were located around the joint space. Having completed this, the participants were introduced to the experimental task using the same SKATS model on which they had trained. This required them to navigate the joint space, locate (view) and touch (contact with the probe) five white spheres placed within the VE (see Figure 4). Upon contact the spheres turned red.

INSERT FIGURE 4 ABOUT HERE

The participants were instructed to avoid collisions between the arthroscope tip and the joint surfaces during the task. The tip of the real arthroscope (on which the experimental arthroscope is based) is machined at a 30 degree angle to increase the field of view, this results in a sharp metal edge. A common problem for trainees is scuffing of the joint surfaces with this edge which can lead to arthritis of the joint in later life. The SKATS system provides visual feedback in the form a red out of the screen (as seen in Figure 4), to inform the user that they have contacted the surface in this way.

Each participant in group 1 completed the task twice on SKATS A and then once on SKATS B. Group 2 completed it twice on SKATS B and then once on SKATS A (as indicated in Table 1).

INSERT TABLE 1 ABOUT HERE

Three different arrangements of the spheres were applied randomly across the three trials. Following task completion the participants were given a demographics and feedback questionnaire to complete regarding their awareness of the differences between the two systems and debriefed regarding the aims of the experiment.

Performance data and metrics

SKATS automatically collects performance data. Position and orientation data for each tool and bone are recorded in a binary file to allow replaying of the training session and performance assessment. A variety of different metrics are currently under development to provide comprehensive performance feedback. For this experiment the performance data was analyzed and assessed based on:

1. Success of task completion – based on the number of loose bodies probed
2. Efficiency of task completion – based on task completion time and the path length of the arthroscope and probe as they were moved around the joint
3. Errors – the number of times the tip of the arthroscope contacted the cartilage surface (defined as tip contacts)

2.2 Results

A summary of the data collected from each system across the participant groups is provided in Table 2.

INSERT TABLE 2 ABOUT HERE

Comparison of systems

The data was analyzed to compare user performance on the two systems. The graphs in Figure 5 indicate that across all of the trials and participants, performance on SKATS A took longer and resulted in longer arthroscope and probe path lengths. Statistical analysis did not indicate a significant effect.

INSERT FIGURE 5 ABOUT HERE

When a comparison was made between each system based on trial two (Group 1 using SKATS A and group 2 using SKATS B), a main effect was found. Statistical analysis using the Mann-Whitney test indicated a significant difference in terms of task completion times [$z= -2.302$, $p<0.05$] and probe path length [$z=-2.747$; $p< 0.01$].

Transfer between systems.

The results from trial 2 and trial 3 (where the participants went from performing the task on a familiar system to the alternate system) were considered to determine if performance levels could be transferred between the systems. The results in Figure 6 suggest that the performance of those in Group 1 stayed constant or marginally improved as they moved from SKATS A to SKATS B. In contrast the performance of Group 2 indicated a decline in performance when they began using SKATS A (containing the bone), in terms of longer task completion times, arthroscope and probe path lengths. A significant interaction [$F(1,12) = 4.836$; $p < 0.05$] was found between trial and experimental group using a mixed design ANOVA.

INSERT FIGURE 6 ABOUT HERE

User feedback

In a post-task questionnaire the participants were asked about their awareness of the differences between the two SKATS models, the responses are shown in Figure 7.

INSERT FIGURE 7 ABOUT HERE

2.3 Discussion and conclusions

The experimental results suggest differences in participant performance on the two SKATS systems. Specifically SKATS A, containing the physical tibia, fibia and cartilage surfaces appears to have resulted in less efficient performance, through lower task completion times and longer instrument path lengths. The bone models provide physical barriers to instrument movement forcing the user to navigate around them thus increasing time and path length. Without the bones, the participants are able to pass through the virtual structures and locate and probe the loose bodies (spheres) with more ease.

Furthermore performance on SKATS A did not readily transfer to SKATS B. When Group 2 transferred from using the system without the bones to SKATS A, task completion times and instrument path lengths were seen to increase. In contrast, Group 1 participants showed little change in performance, only marginal shortening of arthroscope path length and task completion time.

The user feedback also provided support for the assertion that the addition of the bone altered the task. The majority of the participants were aware of the bone and in which leg it was present. They reported that the task was easier when the physical bone was not present. However, five out of the fourteen participants were unaware of the physical bone being present.

As a whole the results suggest that the two systems have differing task requirements and invoke different levels of performance. This emphasizes the importance of providing haptic feedback in a training environment where navigation around structures is a fundamental part of the operative procedure, particularly where there is risk presented through inappropriate movement of the arthroscope.

Having compared the two versions of SKATS and demonstrated the effect of adding the physical models, SKATS A (tactile augmentation model) was taken forward for further testing with potential end-users.

3. EXPERIMENT 2: EVALUATING THE SYSTEM WITH SURGEONS

It was aimed to investigate whether performance on the system could allow differentiation of surgical expertise. This would indicate construct validity or the extent to which the simulator is tapping into the intended underlying abilities. Feedback on the system's face validity was also collected. It was hypothesized that:

H1. Task performance (indicated by the SKATS metrics) would vary based on surgical experience

H2. Consultant surgeons would complete the task more efficiently and with fewer errors than novices.

3.1 Method

Participants

19 participants completed the experiment. The group comprised of 4 consultant surgeons (who had completed more than 100 knee arthroscopy procedures), 5 registrars (who had completed between 20 and 100) and 10 untrained engineering students who had no experience of arthroscopy.

Equipment

SKATS A including the physical tibia, fibia and cartilage surfaces was used throughout the testing. The untrained participants were given standardised training on the anatomy of the knee, the aims of arthroscopy and how the surgical instruments and leg could be manipulated to view the joint space.

Each participant completed the familiarisation task of navigating the knee joint and locating the numbers 0 to 7 placed around the knee (as described in the previous experiment). They then completed the experimental task which, as before, involved navigation of the joint space to locate and probe five spheres placed within the virtual knee. The participants were instructed to avoid collisions between the arthroscope tip and the joint surfaces. Performance was again assessed based on task completion time, arthroscope and probe path lengths and arthroscope tip contacts.

Following the experiment the surgeons were asked to complete a short questionnaire giving feedback on the system. This aimed at gauging the likely acceptance of the system as a training tool and identifying features requiring further development. They were asked to respond to the following four statements based on a five point likert scale (1 Strongly disagree, 2 Disagree, 3 Unsure, 4 Agree, 5 Strongly agree).

1. The system is beneficial to the introduction of basic skills e.g. triangulation, navigation and orientation within the joint
2. The visual representation of the joint provides sufficient realism for the training of basic skills
3. The physical limb model provides sufficient realism for the training of basic skills
4. I would use the system for training (or recommend it for use) if it were available.

3.2 Results

Due to the small and varying sample sizes in this initial study, statistical comparisons were not performed; instead trends in the data and experimental observations will be discussed.

Comparison of user performance

The data was analyzed to consider the differences in performance of the three participant groups; this is illustrated in Figure 8. Examination of the graphs shows the consultants completed the task more rapidly, and with the shortest probe path length. There is little variability in the mean arthroscope path length across the three groups. The most errors through scope tip contacts were evident within the consultant group, with the inexperienced student group producing the fewest.

INSERT FIGURE 8 HERE

User feedback

The results of the feedback questionnaire completed by 8 out of the 9 surgical participants are shown in Table 3.

INSERT TABLE 3 ABOUT HERE

3.3 Discussion and conclusions

Comparison of user performance

The consultant surgeons were working more efficiently in terms of mean task completion time and shorter mean probe path length. The students mean probe path length was the longest. They had difficulty triangulating the two instruments and making contact with the spheres when presented with a 2D image of a 3D space. This is one of the challenges facing surgical trainees that the system aims to overcome.

The registrars took longest to complete the task, although their average probe path length was shorter than that of the students. Observation of performance suggested the registrars took time to reach the spheres with controlled movement, whilst the students were more likely to make more rapid swiping movements to make contact with the spheres. The instrument handling skills developed with expertise are evident from the consultants' shorter probe path lengths; their time was spent viewing the joint space rather than manipulating the probe.

Interestingly the students made fewer arthroscope tip contact errors than the consultant surgeons. This is thought to reflect understanding of the wider task requirements. Through observation it was apparent that the students positioned the arthroscope further away from the knee surfaces and had a more global view of the knee. In contrast the surgeons got closer to the surfaces to examine them in detail moving both instruments within the 3D space.

The differentiation of surgical expertise through simulator usage suggests that elements of surgical skill are targeted through the system. This indicates a level of construct validity warranting further trials to establish this reliably with a larger cohort.

User feedback

The results from the feedback questionnaire were largely positive with all of the surgeons agreeing the system to be beneficial to the introduction of basic skills and recommending use of the system for training. When asked if the visual representation of the joint provided sufficient realism for the training of basic skills, 6 out of the 8 respondents agreed, with 2 indicating that they were unsure. When asked if the physical limb model provided sufficient realism for the training of basic skills the consultants were more positive than the registrars; 2 of the registrars being unsure and 2 disagreeing. Further discussion with the participants suggested this related to the absence of physical models for some knee structures. Only the tibia, fibia and articular cartilage were represented and other structures, e.g. the cruciate ligaments were missing. It is interesting that the registrars were more critical of this element. This may be because having acquired basic skills they want to use SKATS for more advanced skills, whilst the consultants value the system for the first introduction to arthroscopy skills.

5. DISCUSSION

This paper has described the re-development of SKATS through the use of tactile augmentation to form a mixed reality environment. The two experiments have looked at the viability of this approach in taking forward SKATS as a training tool. The following issues have been considered:

1. The effect haptic augmentation has on performance
2. Whether the system is able to differentiate expert and novice surgical performance
3. How users feel about the system

The results of experiment 1 have highlighted the performance differences resulting from the addition of physical structures into SKATS. The differences suggest disparity in the skill acquisition that would result from training on a system without haptic feedback to one with, or in fact the real world. A system without haptic feedback simplifies the navigation element of the task. Tactile augmentation of SKATS is more likely to reduce patient risk as it prepares the user more appropriately for the real world task.

The differentiation of expert and novice performance demonstrated through experiment 2 suggests that the tactile augmentation SKATS carries a basic level of construct validity. This, along with the feedback received from the participants rationalizes continued development and validation of the mixed reality training environment. Following initial acquisition on a VR simulator, skills should be readily transferable into the operating theatre without the trainee having false confidence in their ability. Our future testing will look at the transferability of the skills developed on SKATS.

The mixed reality approach overcomes some of the technical and fiscal challenges of mechanically generated haptic feedback. However it does introduce other problems. Whether the system design is accepted by the individual user, the trainer and the organization is crucial to the system's long term viability. The level of fidelity provided must consider user expectations for successful adoption. The surgical feedback highlighted the importance of providing haptic feedback from all of the knee structures and not just the bone. Tactile augmentation is an effective solution for rigid bodies such as bone that can have they entire geometry mapped within the VE. However to map non-rigid structures e.g. meniscus and ligaments, presents a significant challenge requiring accurate shape and positional information. The manipulation of the physical leg and collisions with the tools results in the non-rigid components being placed in an unlimited number of configurations. The required technology to track such deformations and movements may in fact make a fully haptic simulator more cost effective.

Another of the developmental challenges is the simulation of pathological features. In a fully virtual environment this would be relatively straightforward and achieved through computer-based changes in the visual and force feedback properties. In the tactile augmentation model it would require the permanent presence of the condition, or repeated replacement of parts of the physical model. In response to these two challenges the authors are investigating sensory enhancements as an alternative strategy. Biocca et al. describe sensory enhancements as occurring when stimulation in one sensory channel leads to an illusion or enhancement of stimulation in another, for example the illusion of a haptic sensation (e.g. texture) or enhanced fidelity from visual cues [24]. Support for the use of visual cues to enhance haptic perception elsewhere [25][26][27][28]. For certain knee structures and conditions, where only subtle changes are observed, it may be possible to simulate fine variations through the use of visual cues, which technologically we have more control over in the VE.

The varying degrees of awareness of the physical bone in Experiment 1 lends support to the reliance on visual cues by novice users which may be utilized within the system design [10].

The approach taken to further development of SKATS is very much based on necessary fidelity [10] and understanding perceptual abilities and limitations within the training domain. Our understanding of haptic perception within virtual and mixed reality environments, particularly for minimal access surgery is still limited. High end fidelity is likely to be unnecessary to acquire certain skills but design decisions need to be balanced against user expectations. Our future work will make use of SKATS as a platform for experimental investigation of users' haptic requirements as well as continuing system validation.

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