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ORIGINAL ARTICLE

# Beyond the visuals: tactile augmentation and sensory enhancement in an arthroscopy simulator

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**Abstract** This paper considers tactile augmentation, the addition of a physical object within a virtual environment (VE) to provide haptic feedback. The resulting mixed reality environment is limited in terms of the ease with which changes can be made to the haptic properties of objects within it. Therefore sensory enhancements or illusions that make use of visual cues to alter the perceived hardness of a physical object allowing variation in haptic properties are considered. Experimental work demonstrates that a single physical surface can be made to 'feel' both softer and harder than it is in reality by the accompanying visual information presented. The strong impact visual cues have on the overall perception of object hardness, indicates haptic accuracy may not be essential for a realistic virtual experience. The experimental results are related specifically to the development of a VE for surgical training; however, the conclusions drawn are broadly applicable to the simulation of touch and the understanding of haptic perception within VEs.

**Keywords** Tactile augmentation · Sensory enhancement · Sensory illusion · Surgical simulator · Mixed reality



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## 1 Introduction

This paper explores tactile augmentation as a means to generating a sense of touch within a virtual environment (VE) given the challenges of accurately simulating the haptic properties of virtual materials.

Tactile augmentation involves the addition of physical objects into a VE. It is cheaper and simpler than incorporating a haptic device, and more realistic than a purely visual environment. However, the incorporation of a real object limits the potential variability of the haptic environment. Therefore the potential of using visual cues to allow alteration of the physical object is demonstrated.

It is argued that the interrelated nature of our sensory systems and the dominance of the visual sensory channel (Welch and Warren 1986) can be used to support simulation design. The utilization of visual cues to create a 'sensory illusion or enhancement' and alter the haptic experience by making a surface 'feel' harder or softer than it is in reality is explored. This is significant given the relative ease of producing high fidelity visual cues compared to accurate haptic feedback.

Sensory enhancements are demonstrated as a means to create haptic variability and improve the realism offered by tactile augmentation. The research informs the design of the Sheffield knee arthroscopy training system (SKATS), a virtual reality (VR) simulator for training knee surgery skills.

### 1.1 The Sheffield knee arthroscopy training system

SKATS (illustrated in Fig. 1) is a VE for training basic skills associated with knee arthroscopy (keyhole surgery of the joint) (McCarthy 2000).

Arthroscopy involves the surgeon working with an arthroscope (camera) for viewing the joint, and various instruments including a probe, for the manipulation of structures resulting in an impoverished sensory environment. All procedures involve coordination of the patient's limb position, vision and tool movement, to navigate the joint and examine structures to ascertain the condition of the knee.

The original version of SKATS was PC-based and included a hollow plastic model of the limb, replica tools and a monitor displaying the virtual internal view of the knee joint via a monitor (McCarthy and Hollands 1998). A 3D computer-generated environment provided a real-time, interactive simulation of the tissue.

The lack of haptic feedback was a shortcoming of the system as only a restricted understanding of virtual tissue properties was offered and it was possible to pass through apparently solid structures. Furthermore research shows that multi-sensory information improves the quality of perception and the sense of presence offered by a VE (Klatzky and Lederman 2002; Schultz and Petersik 1994; Boshra and Zhang 1994). 'Touching' a real or virtual object and receiving a multi-modality sensation, (haptic as well as visual cues), results in a more compelling and immersive experience and improves task performance (England 1995; Burdea and Coiffet 1994; Srinivasan and Basdogan 1997; Petzold et al. 2004).

**Fig. 1** The SKATS system

### 1.2 Haptic feedback

Mechanical generation of haptic feedback is the approach taken to the development of physical resistance in many surgical simulations (Niemeyer et al. 2004; Agus et al. 2003; Webster et al. 2001). However, the technical challenges and expense involved are well documented (Srinivasan 1996; Bro-Nielson 1997; Chen and Marcus 1998; Zivanovic et al. 2003). Most available devices are not technically advanced enough for this application, where to meet the bimanual nature of the task, two sufficiently compact devices would need to fit within a manipulable limb model and generate a large range of forces to cater for different tissue properties (Zivanovic et al. 2003; Basdogan et al. 2004).

Psychological research into training simulator use suggests that accurate haptic modelling is not always necessary. Simulator design is always approximate and adequacy depends on the limits of human perception and performance (Srinivasan and Basdogan 1997; Tan 1994). Therefore, haptic feedback needs to match human abilities and limitations in terms of sensory perception and skill acquisition within the context of the real task rather than accurately replicating the environment and actual forces (Moody et al. 2003). Here we are interested in understanding more about necessary haptic accuracy to inform simulator design. This is considered in respect to tactile augmentation, an alternative to mechanically generated haptic feedback.

### 1.3 Tactile augmentation

Tactile augmentation is a form of mixed reality whereby a synthetic model is employed within a virtual space to provided tactile cues (Hoffman et al. 1996; Milgram 1994). Tactile augmentation is believed to improve the realism and quality of a VE, enhance the sense of presence over a purely visual representation (Hoffman et al. 1996) and improve human performance (Hoffman 1998; Wang 2000). It is proposed to redevelop SKATS through tactile augmentation and integrate a physical knee model within the VE. It is assumed that contact with structural elements of the knee will support the development of basic surgical skills, boost user satisfaction, and offer a platform for



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further investigation of the necessary haptic requirements of the task domain.

One major shortcoming of tactile augmentation over mechanically generated haptic feedback is the lack of system flexibility. In a fully VE making changes to the knee environment, (e.g. introducing pathologies such as chondral defects), would be straightforward through computer-based changes in visual and force feedback properties. In a tactile augmentation model this would require the permanent presence of the condition, or replacement of the physical model. Sensory enhancements are posited as a potential means to address this. It may be possible to create variation, and increase the fidelity of the model by utilizing visual cues and characteristics of sensory perception.

### 1.4 Sensory interaction and dominance

The senses do not work independently but are interrelated, active systems. Touch cues are gathered and combined with information from the other senses to form a complex impression (Gibson 1966). Studies of perception indicate that stimuli in one modality are not only combined with, but can also influence the experience of cues from another (Welch and Warren 1980; Ernst 2002). Welch and Warren describe 'visual capture' whereby the dominance of the visual sensory channel suggests that it can influence the interpretation of haptic information. When a visual and a haptic cue are in slight contradiction (for example, a surface may look harder than it feels), the visual cue overpowers the haptic information (Srinivasan and Basdogan 1997; Ernst 2002; Ellis and Lederman 1993). Klatzky and Lederman (2002) emphasize that the success of such an effect is determined by the relative appropriateness of the task for the sensory modality. The appropriateness, defined in terms of accuracy, precision and cue utilization, determines how the individual distributes attention amongst the available sources of information. For example, if a task requires fine spatial resolution, vision is likely to dominate. However, touch is likely to perform as well in discriminating differences in surface roughness.

### 1.5 Pseudo-haptic feedback: sensory illusions and enhancements

These ideas have been applied to VR where the dominance of vision in the performance of some real world tasks could compensate for shortcomings in haptic technology. More advanced visual simulation technology could be used to augment impoverished haptic feedback improving the overall fidelity of a VE. Lindeman et al. (Lindeman et al. 2002) argue that simple haptic feedback combined with high-quality visual images or 'pseudo-haptics' could create a comparable sense of contact to that produced by more expensive haptic devices. Pseudo-haptics' are '*systems providing haptic information generated, augmented or modified, by the influence of another sensory modality*' (Lecuyer et al. 2001, p 115). Biocca et al. (2001) similarly describe sensory illusions and enhancements occurring when stimulation in one sensory channel leads to the perception of stimulation in another, such as the illusion of a haptic sensation from visual or audio cues (Petzold et al. 2004; DiFranco et al. 1997).

Experiments by Lecuyer et al. (Lecuyer et al. 2000a, b) have investigated haptic illusions through the manipulation of virtual springs using the Spaceball, a passive, isometric device providing a constant level of force feedback, and varying levels of visual feedback. The springs were perceived to deform varyingly, with force cues comparable to real ones, despite little movement of the user's fingers. The perception relied on visual displacement rather than the 'feel' of the device; the participants needed to feel resistance, but did not need the force to be accurate.

Studies by Srinivasan et al. (1996) and Durfee et al. (1997) have shown similar effects when using haptic devices and an increasing misperception of stiffness with greater mismatch between visual and haptic information. Miner et al. (1996) have shown that visual stimuli can be used to influence perception of both smaller and a larger forces when using a haptic interface (Miner et al. 1996) and the illusion is most effective when the visual and haptic cues specified are non-contradictory (Hillis et al. 2002).

The discussed research suggests that haptic illusions using visual stimuli can be exploited to enhance the haptic experience. Here, we build upon this to consider whether sensory enhancements can be used to influence the haptic perception generated through tactile augmentation.

## 2 Aims and hypotheses

Whilst of wider interest to VR research and haptic simulation, the aim of this research was to consider how sensory enhancements might be used in conjunction with tactile augmentation to improve the realism of SKATS.

A purpose-built test rig developed at the University of Sheffield was used. As well as providing a platform to align and calibrate the real and virtual model, and for developing advanced tissue deformation techniques, the system provides an environment for carrying out controlled experimentation relating to force perception. The rig and visual interface were simple (as opposed to realistic tissue graphics within a surgical context) to avoid introducing confounding effects. This is in line with research carried out by Biocca et al. (2001) who found the success of the illusion was not affected by whether the environment was





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composed of meaningful, vivid human organs or abstract geometric primitives.

The experimental approach taken is novel in several ways. Firstly, it is specifically related to minimal access (keyhole) surgery where contact with surfaces is indirect and force feedback is received via a surgical probe. Secondly, the studies previously discussed describe the enhancement of force perception using an isotonic device (Lecuyer 2000b) or haptic interface (Petzold et al. 2004; Srinivasan 1996; DiFranco et al. 1997; Durfee et al. 1997; Miner et al. 1996; Hillis et al. 2002). Here, it is considered in relation to a fixed physical object as is relevant to tactile augmentation. It is hypothesized that:

a. The perceived hardness of a structure can be enhanced through its visual appearance
b. The effect will be dependent upon the discrepancy between the visual and haptic information

## 3 Method

### 3.1 Participants

Twenty participants took part in the experiment, ten female and ten male. They had a mean age of thirty-three years (range 22–53). Sixteen were right handed and the remainder left hand dominant. A within-subjects design was applied in which all participants completed testing in each condition.

### 3.2 Equipment

A physical rig and visual simulation were designed and produced at the University of Sheffield (pictured in Fig. 2a). The hardware rig consisted of a box (Fig. 2b) containing a plate of 6 identical pads made of silicone sheet with the same material properties and arranged in the formation shown in Fig. 2c. The silicone sheet was chosen by an orthopedic surgeon to resemble the properties of pathological knee cartilage thereby relating to the wider interests of our research. A probe could be inserted into the box through a small hole to contact the silicone pads physically without direct visualization.

The VE was written in Microsoft Visual C++ using WorldToolkit (Sense8 Inc, San Rafael, California) and run on a laptop. The user was presented with an image on the monitor, representing the plate of physical structures within the box, as shown in Fig. 2a. The position and orientation of the VE were registered (mapped) to the physical model, and a FASTRAK system (Polhemus, Colchester, Vermont) used to track the position and orientation of the real



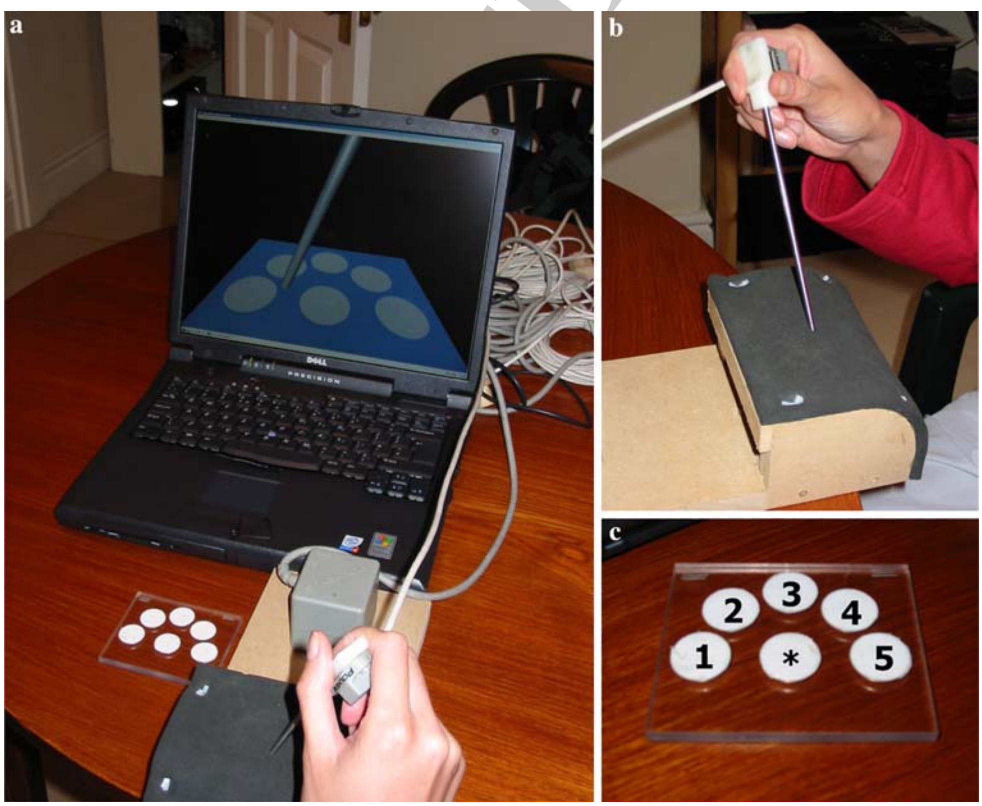


**Fig. 2** Experimental rig and virtual environment. **a** The experimental set-up and virtual environment. **b** The box containing the plate of silicone pads (**c**)



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probing instrument in space. Contact between the real probe and silicone pad, resulted in deformation of the virtual surface in response to contact with the virtual probe. Although the physical pads provided uniform actual force feedback to the user, the visual deformation in the VE was varied.

### 3.3 Procedure

Each participant was given standardized instructions and a few minutes to familiarize themselves with the task and the VE. The participants were asked to probe, using their dominant hand, each of the five target pads displayed on the monitor (1–5 in Fig. 2c) and compare it to a sixth control pad (* in Fig. 2c). They were instructed to touch each target and then the control pad once and make a decision as to whether the target felt harder, softer or the same as the control. The experimenter recorded the verbal response.

After each of the five target pads was compared to the control (i.e. one set of trials), the experimenter adjusted the visual parameters. The physical plate in the box simulator was also changed for an identical plate to suggest that the surfaces were not constant across the experiment. Whilst all of the pads had the same force feedback properties (described to the participants as hardness) there were five visual conditions based upon the level of deformation in the VE.

The visual deformation of the control pad and condition 3 were appropriate for the material properties. However the level of visual deformation was adjusted for conditions 1, 2, 4 and 5 as shown in Table 1.

In condition 1 the level of visual deformation was reduced by a factor of two to suggest a harder surface. In contrast, in condition 5 the visual deformation was increased, so that the surface appeared to be softer. The surface of the virtual plate was constructed of a set of connecting nodes forming polygons. As a polygon intersection algorithm detected a collision between the probe tip and virtual plate surface, nodes belonging to the intersected polygon belonging to the plate were displaced in relation to the tracked displacement of the probe tip. The level of deformation was determined by a scaling (or deformation) factor (K) applied to the measured displacement ($y$) in the vertical direction calculated as: $\frac{1}{\log 10}$ K. Thus, a scaling of 0.5 reduced the visual deformation by one-half or could be considered to have increased the stiffness by a factor of 2, while a scaling of 2 doubled the deformation or softness. The lighting model was updated accordingly to behave appropriately for the deformation. The scaling was informed by a small pilot study to determine the boundaries of realistic deformation.

The participants were presented with the five pads for comparison ten times, completing fifty trials in total. For each participant the experiment lasted between 20 and 30 min. The visual hardness was randomized across the pad position, trials and participants. The independent variable manipulated was the level of visual deformation. The dependent variable was the perceived hardness of the target pad compared to the control.

**Table 1** Experimental visual conditions

| Condition | Visual simulation and scaling | | |
|---|---|---|---|
| | K | $\frac{1}{\log 10} K$ | Intended visual illusion |
| Control pad | $K = 0$ | 1 (Appropriate) | |
| 1 | $K = -0.3$ | 0.5 (100% harder) | Very hard |
| 2 | $K = -0.1$ | 0.79 (25 % harder) | Harder |
| 3 | $K = 0$ | 1 (Appropriate) | Same |
| 4 | $K = 0.1$ | 1.26 (20% softer) | Soft |
| 5 | $K = 0.2$ | 1.58 (35% softer) | Very soft |

## 4 Results

In describing the results, responses were termed as correct or incorrect. A correct response was defined as the participant conforming to the visual enhancement. That is, the response was correct in terms of the visual appearance of the pad, not the haptic properties (which would have resulted in the response 'the same' for each trial).

The mean number of correct responses and the type of incorrect responses across participants for each condition are provided in Table 2.

Figure 3 illustrates the percentage of responses overall. There were more correct than incorrect responses indicating that the participants were influenced by the visual enhancements. The application of the Binomial test supported this conclusion ($P < 0.01$).

**Table 2** Responses provided for each condition

| Condition | Mean number of responses for each condition (/10) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Correct | | Incorrect | | | | | |
| | | | Same | | Harder | | Softer | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 1 very hard | 7.3 | 2.59 | 1.6 | 1.85 | | | 1.1 | 1.77 |
| 2 hard | 3.6 | 2.23 | 3.45 | 2.33 | | | 2.95 | 2.14 |
| 3 same | 4.25 | 2.26 | | | 1.4 | 1.47 | 4.35 | 2.46 |
| 4 soft | 6.8 | 2.28 | 2.3 | 1.95 | 0.9 | 1.07 | | |
| 5 very soft | 7.8 | 1.43 | 1.7 | 1.54 | 0.5 | 1.05 | | |





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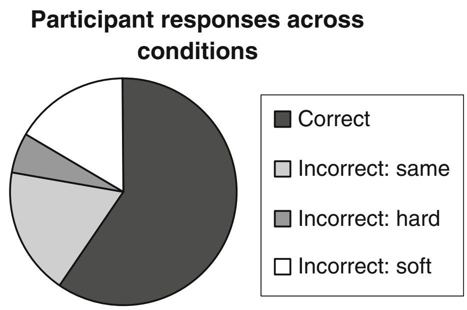


**Fig. 3** Chart indicating the participant's responses

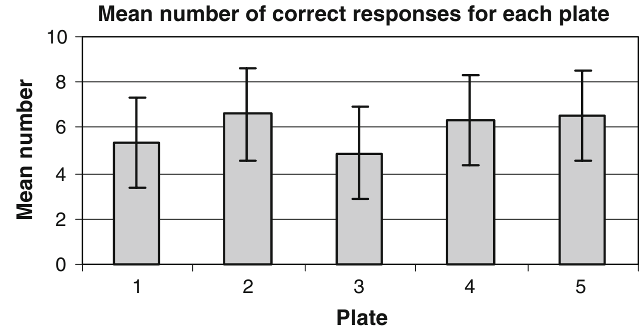


**Fig. 5** Mean number of correct judgments for each pad position

The mean values in Table 2 show that more correct responses were given when there was a greater disparity between the visual and haptic cues (i.e. in conditions 1 and 5). There were fewest correct responses when simulating a hard surface in condition 2. This suggests that an illusion of a softer surface can be created more easily than a harder surface with less proportional change of the visual environment.

A two way ANOVA was used to analyze the effect of the two independent variables; condition (the level of visual deformation) and plate position. Application of the Mauchly statistic gave a $P$ value for plate of 0.358 and of condition of 0.368 indicating no heterogeneity of covariance indicating appropriate use of the $F$ test.

The analysis indicated a main effect of condition [$F$ (4, 76) = 14.99; $P < 0.01$]. Therefore it can be concluded that the amount of visual deformation had an effect on the response to the visual stimuli and the effectiveness of the enhancement. As Fig. 4 suggests there were more correct responses for conditions 1, 4 and 5.

Further analysis of the incorrect responses (see Fig. 4) suggested that when an incorrect response was given in a soft condition, the plate was more often identified as being the same rather than harder than the control. Post hoc analysis using the Binomial test supported this statistically for conditions 4 ($P < 0.01$) and 5 ($P < 0.01$). In condition 3, the plate was more often identified as being softer, than correctly identified as being the same, or incorrectly as harder ($P < 0.01$). In condition 1 and 2 there was less difference in the type of incorrect response given.

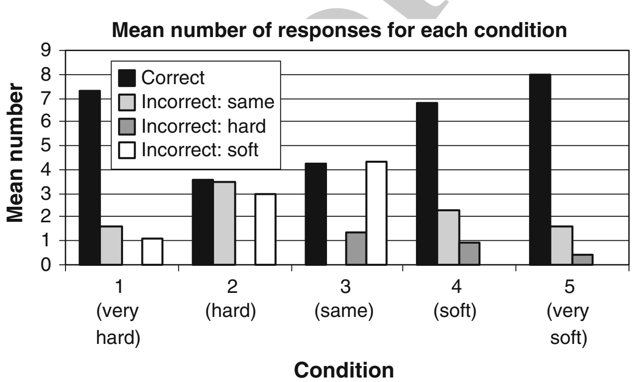


**Fig. 4** Graph of the mean type of response for each condition

Figure 5 illustrates the correct responses by pad position on the plate. The two way ANOVA indicated a main effect of plate position [$F$ (4, 76) = 4.194; $P < 0.01$)]. A post hoc Bonferroni comparison revealed the difference to lie between the responses given for pad 3 compared to pad 2 ($P < 0.05$) and pad 5 ($P < 0.05$). An interaction between pad position and condition [$F$ (4,304) = 2.728, $P < 0.01$] was also indicated.

## 5 Discussion

The experiment produced two main findings. Firstly, participants were influenced in their perception of hardness by the presentation of visual information. Secondly, the success of the enhancement varied based on the discrepancy between the visual and haptic information. These findings are discussed further in the following sections.

### 5.1 Effect of visual enhancement on haptic perception

The results indicate that the participants were influenced by the visual stimuli in the judgments they made. The expected response for each comparison (based on the haptic properties) was that the target and the control were of the same hardness. Any other response suggested that the participants were responding to the enhancement created through the visual deformation of the VE. The results supported the hypothesis that some users experience sensory enhancements and respond to the visual stimuli when presented with discrepant visual and haptic information.

### 5.2 Effect of condition (degree of visual and haptic displacement)

The effectiveness of the haptic illusion was found to vary based upon the level of visual deformation (condition).





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Decreased deformation to give the illusion of a harder surface proved effective in condition 1 (100% harder), but unsuccessful in condition 2 (25% harder). In conditions 4 (20% softer) and 5 (35% softer) increasing the level of deformation to enhance the softness of the surface proved successful. When the target (condition 3) and control plate both had the same (appropriate) level of visual deformation for the physical object, the participants could not always determine this and in fact more often identified the target as being softer than the control.

Further analysis of the incorrect responses indicated that when an incorrect response was given for increased visual deformation (the softer conditions 4,5) the response tended to be that the plate was the same as the control rather than providing the opposite response (i.e. that the target plate was harder). In conditions 1 and 2 there was little difference in the type of incorrect response given, but more often the target was identified as being the same not softer.

The results in condition 2 (25% harder) and 4 (20% softer) are interesting. Whilst conditions 2 and 4 are created through a similar proportionate change in visual deformation, in condition 4 the participants were convinced by the enhancement but in condition 2 they were not; often stating that the plate was the same as the control. This suggests greater sensitivity to an increase in deformation compared with a reduction. In other words, a larger proportionate visual change is required to enhance the hardness of a surface than to soften it.

There will of course be limits to the effect; where the visual change is too small to be discernable and an upper threshold where the mismatch between haptic and visual cues is too large to be convincing. Further investigation of the perceptual boundaries and appropriate scaling to understand and achieve the desired enhancement effect is required.

### 5.3 Effect of plate position

The technique used to create the visual enhancement was the degree of surface deformation. The experimenter observed that due to the angle of probe contact determined by the pad position on the plate (Fig. 2c), the appearance of the deformation varied. Therefore a comparison of correct responses based on pad position was performed. This revealed an effect of position and a significant interaction between the pad position and condition.

This is explained by the positioning of the light source causing varying visibility of the reflection effect at different angles. The light position in the VE is fixed and is directed straight onto the control pad and pad 3. In the case of pads 1, 2, 4 and 5 the light is cast at an angle and is reflected differently. The direct angle in the case of pad 3 and the control reduces the amount of reflection and visual information and appears to have masked some of the enhancement effect. These effects are demonstrated in Fig. 6.

Since the presentation of the conditions was randomized across the pads this does not have major implications for the conclusions of this study. Furthermore the effect is typical of interaction within a real environment where visual cues are affected by the angle of contact with an object and the position of the light source. In a repeat of this study, moving the position of the control pad should moderate this effect. Further consideration of how this effect influences perception in the real surgical environment would be of value. (Fig. 6)

## 6 Implications for ve design

The findings have demonstrated the potential of visual cues through sensory enhancement to alter the perception of a physical surface. It has been shown that a surface can be made to feel either harder or softer through the provision of visual information. This could be useful for the incorporation of simple, cheap yet effective haptic feedback into VEs through tactile augmentation, as well as informing haptic device development. The results imply that haptic accuracy is not essential, as humans in an indirect contact

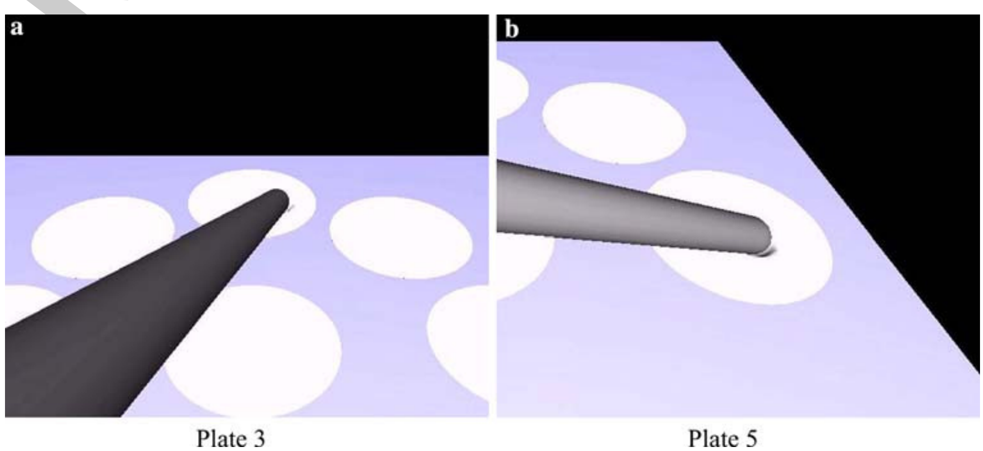


**Fig. 6** Screen shots of the VE demonstrating the effect of the pad position on the deformation effect





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task do not display a strong reliance on the actual haptic properties of a surface. They are easily led by a visual image and the interaction between visual and haptic information.

The experiment was carried out to inform the design of SKATS. It is aimed to provide an improved sensory perception from the complete simulator experience as opposed to a strong technical development focus. A human-centered approach is taken rather than one focused on exact replication of the surgical environment. Whatever form the haptic display takes, it should be designed in conjunction with visual feedback and knowledge of human performance characteristics.

### 6.1 Viability of tactile augmentation

Tactile augmentation has been described as an alternative to a mechanical haptic interface. It is a simpler and cheaper means to provide resistance. This supports the project aim of producing a simulator that is commercially viable within a hospital setting. Whilst this suits the immediate design requirements, long-term the primary disadvantage is the challenge of simulating any variation in the force feedback offered, for example pathology within the knee. Therefore, sensory enhancements have been discussed as a means to adjust the force feedback parameters and improve the fidelity of the physical models by altering the combined sensory experience.

The experimental work has shown that the perceived hardness of a physical surface can be altered through variation in the visual information provided. It is argued that skewing the relationship between the haptic and visual displays can enhance the haptic feedback that would be offered by a physical simulation alone. The indication from the results that hard surfaces can be successfully manipulated to appear soft is particularly useful for the simulation of specific pathology within the knee (chondral defects) where there is seen to be a softening of the cartilage surfaces.

Before such information can be assimilated into a system, the limits of the effect should be considered. The results suggest that the degree of visual deformation was important in determining whether the enhancement was successful in softening or hardening the surface. Further experimental work is necessary to establish the parameters of this effect. Subjective evaluation of the effectiveness of the illusion should also be made, as it is unclear whether the tendency of the participants to respond to the visual illusion was the result of successful sensory enhancement or whether it was a conscious decision to respond to the visual information presented.

The scenario considered in this experiment is a simplistic representation of a probing task performed during knee arthroscopy. The focus of the experiment was specifically to differentiate the level of force feedback (described to the participants as hardness) between two items. However, in the training of a procedure, task performance is far more complex with combined sensory inputs and attention allocation to multiple tasks. Future research should consider whether, when attention is allocated to more complex task completion, the success of haptic enhancements remains. It is suggested that success is likely to be greater within a multi-sensory training environment employed by users motivated to 'believe in' the VE and learn a surgical procedure.

### 6.2 Implications for haptic devices

This research has implications not just for tactile augmentation, but also for the necessary accuracy of haptic device design. As discussed previously, there are a number of technical challenges in the design of mechanical haptic feedback devices based on the replication of tissue properties and surgical force applications. Nevertheless, from a human factors approach, through an understanding of the characteristics of the haptic system (i.e. its susceptibility to sensory enhancements and its combinatorial relationship with other sensory systems), techniques may be developed to exploit these characteristics whilst creating a 'realistic' haptic experience. For example, adjusting the visual parameters of objects may increase the range of properties that can be simulated without accurate force modeling, thereby lowering the specification of the required haptic device. Future work on SKATS aims to extend these ideas to mechanical haptic device development, as it is believed that the design of visual and haptic feedback devices should be undertaken in conjunction with each other for the formation of a complete sensory experience.

## 7 Conclusions

The aim of this paper has to been to consider the use of tactile augmentation and sensory enhancements in VR design. SKATS is undergoing iterative development to provide visual and physical resistance to movement of surgical tools in response to training requirements and user acceptance criteria. The challenges of developing a suitable haptic device for surgery simulation have been discussed. The SKATS system with tactile augmentation enhances the VE whilst offering a means to collect and validate user requirements. Hence, this acts as a stepping-stone to inform the development of an innovative haptic feedback device to be implemented in a later version, aimed at training a wider skills base including diagnostic tasks.





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This work has offered benefits in terms of the technical development of SKATS. A technique has been developed to align and calibrate the real and virtual model. Furthermore a means to deform a material, such as cartilage, effectively in the VE has been demonstrated. It is recommended that alternative means of varying the visual appearance of hardness such as lighting and textural effects and other more complex paradigms should be investigated for achieving sensory illusions.

The demonstrated combinatorial nature of haptic perception and susceptibility to sensory enhancements could be exploited more broadly in simulator design to improve the viability of tactile augmentation and overcome the challenges of developing accurate haptic feedback. This phenomenon is likely to be valuable to VR research where it is easier to produce high fidelity visual cues than effective haptic feedback devices. However the necessary fidelity of haptic training systems for many applications (including surgery), are not yet known. Whether a mechanical device or a physical structure generates the feel of a surface, a greater understanding is required to ensure functional fidelity and skill transfer.

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