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A Study on the Perception of Haptics in Surgical Simulation

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Abstract. Physically accurate modeling of human soft-tissue is an active research area in surgical simulation. The challenge is compounded by the need for real-time feedback. A good understanding of human haptic interaction can facilitate tissue modeling research, as achieving accuracy beyond perception may be counterproductive. This paper studies human sensitivity to haptic feedback. Specifically, the ability of individuals to consistently recall specific haptic experience, and their ability to perceive latency in haptic feedback. Results suggest that individual performance varies widely, and that this ability is not correlated with clinical experience. A surprising result was the apparent insensitivity of test subjects to significant latency in haptic feedback. The implications of our findings to the design and development of surgical simulators are discussed.

1 Introduction

Surgery training relies on an apprenticeship model. Students traditionally practice on animals, cadavers, and patients. Animals do not have the same anatomy as humans, and their use can raise ethical issues; cadavers cannot provide the correct physiological response; there is a risk to patient safety while the student gains competence. Surgical simulators may address these issues by providing a safe and viable alternative. Virtual patient models can incorporate realistic human anatomy, while both normal and pathological physiology can be simulated. In addition, simulators can provide a structured learning environment with controlled difficulty levels. A survey of the field was recently published [1].

Haptic feedback is essential for realistic training in surgical simulators [2]. Relatively little work has been done on haptic perception, in particular on the relative importance of visual and haptic feedback. Findings from such work can provide insight into the degree of haptic and visual fidelity necessary for realistic training.

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In this paper, we describe two experiments to address this question. The remainder of this section outlines current work done in deformable modeling, haptics, and human-haptic interaction. Section 2 describes our experimental approach, Section 3 contains our results. Sections 4 and 5 provide a discussion of our findings and our conclusions respectively.

1.1 Background

Deformation modeling is an integral part of surgical simulation. Tissues and organs are pliant, and yield when touched. In simulations, both visual and haptic feedback must be accurate. Mass-springs and Finite Element Modeling (FEM) are two of the most widely used methods for simulating deformable tissues in surgical simulation [3, 4, 5]. Mass-spring systems are readily understood and allow for real-time computation of fairly large and complex models. For soft tissue simulation, their main limitation is the difficulty in identifying spring parameters and topology [1, 6]. FEM permits tissue properties to be more accurately modeled by incorporating elasticity theory. The primary disadvantage of FEM is computational complexity, however several methods have been developed to achieve real-time performance using FEM [3, 7].

Surgeons rely on tactile sensory information while operating. Simulating this information is necessary for realistic training. A key issue in integrating haptics into surgical simulators is the update rate required for high fidelity. It is generally accepted that an update rate of at least 1000Hz is required for force reflecting devices such as the PHANToM [1]. This leads to an increased difficulty of achieving physical accuracy in real-time. A common approach is to use simplified or approximate deformation models to achieve haptic update rates [8, 9]. However, its effect on training effectiveness has remained largely unexplored. Understanding more of the human perception of haptics may help developers of simulators to simplify the models used, without harming the perceived realism.

Several studies have investigated the effect of haptics on human operation in virtual environments. Richard *et. al.* conducted an experiment where participants were asked to regulate the exerted force on a virtual object [10]. Results showed that direct haptic feedback was superior to visual or auditory feedback. Best results were achieved when both haptic and redundant auditory feedback were present. Gerovichev, Marayong and Okamura evaluated the effect of visual and haptic feedback in a needle insertion task [11]. Participants were asked to detect skin puncture using haptic and visual cues provided by the simulation. Results showed that a real-time image overlay provided a greater improvement than force feedback. Studies conducted by Oakley *et al* and Brave, Nass, and Sirinian found that haptics are an improvement, but it depends on the context [12, 13]. There is an overall indication that haptics will improve human operation in virtual environments, though much work needs to be done to provide a clear picture of this.

A reoccurring problem in virtual environments is latency. As in Meehan *et al* [14], we use the term to describe a delay between the user's actions and the corresponding effects. Heavy computational loads can affect latency, and

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disturb the user's sense of immersion. Though there have been a number of studies investigating human response to latency, these are usually restricted to graphics, for example [15]. To our knowledge, studies similar to that described in this paper have not been done.

This paper investigates human haptic recall and latency perception in two experiments. These aspects of human ability were chosen for their relevance in surgical simulation. If the clinician's ability to detect and recall haptic feedback is poor, then highly accurate tissue models may be unnecessary. If the human ability to sense haptic latency is poor, the additional delay can be used to refine haptic feedback models.

The studies were performed in the context of a simulated needle insertion. This skill is widely practiced in a variety of medical procedures. They include: phlebotomy, starting intravenous lines, and biopsies. Simulators have been developed for some needle-based procedures [16, 17], and novel methods for modeling needle and tissue deformation have been developed [18].

2 Methods

2.1 Apparatus

The experiments use a CathSim® AccuTouch[3] haptic device attached to a Personal Computer (PC) workstation. The CathSim® consists of a needle wand attached to a magnetic brake. The wand has 3 degrees of freedom (DOF) movement. Pitch, yaw, and insertion/extraction can be detected and reported to the PC. The magnetic brake provides a 1-DOF non force-reflecting haptic feedback as the wand is inserted or extracted. The device can exert ∼4N of resistance. Figure 1 illustrates the device.

The connected workstation provides visual feedback and control for the haptic device. On the display, the user sees a needle positioned above a patch of skin. The user inserts and removes the needle by inserting or removing the wand on the CathSim® device respectively. Visually, deformation of the skin patch is modeled using a mass-spring system. Inserting the needle causes the skin to deform and eventually be punctured (Figure 2(b)). Once punctured, the skin relaxes and assumes its original undeformed condition (Figure 2(c)). Haptically, the user feels an increasing resistance corresponding to increasing deformation of the skin. As the skin is punctured, the CathSim® device simulates the 'pop' by a sudden loss of resistance. This effect is modeled with the following function:

$$FG = \begin{cases} FG_p(\frac{x}{x_p})^2 & \text{if } 0 < x < x_p \\ 0 & otherwise \end{cases}$$

where $FG \in [0,1]$ is the *force gain*, that is the fraction of the maximal force the device is capable of, i.e. $\sim$4N; x is the distance of the needle tip to the insertion point on the undeformed skin surface; x_p is the point of puncture, $FG_p \in [0,1]$

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is a parameter to be varied in the experiment. During extraction $FG = 0$ until the needle is free of the skin. This function is an approximation of findings in other studies, where tissue properties were obtained by measuring stress-strain relations of biological soft-tissue [19, 20].

2.2 Experiment Design

Subjects were medical students, physicians and nurse volunteers who agreed to participate. Each volunteer was given time to become familiar with the setup described in section 2.1. To gage their experience, volunteers were asked to estimate the number of intravenous injections and phlebotomy procedures performed in the last three years.

Haptic Recall. The intent of this experiment is to determine how consistently a haptic experience can be recalled. Results from this experiment can provide insight into the accuracy needed for haptic feedback in medical simulators. In this experiment, 27 volunteers with a wide range of intravenous injection experience participated. The generic needle insertion simulator described in section 2.1 was used. As the focus was consistency, volunteers were not told that the simulation represented any specific procedure. Instead, they were permitted to assume a particular procedure.

Volunteers were then presented with a random initial value of $FG_p \in [0, 1]$. Volunteers were instructed to adjust FG_p until the haptic response was consistent with the assumed procedure. The adjusted FG_p value was then recorded. For each volunteer, the experiment was repeated 10 times.

Haptic Latency. The intent of this experiment was to investigate the volunteer's ability to detect latency between haptic and visual feedback. 28 Volunteers participated. The simulated exercise described in section 2.1 was used. Unlike the previous experiment, a variable delay was introduced between the visual and haptic feedback, i.e., skin deformation upon puncture would be displayed visually before the haptic 'pop' feedback was felt. Each volunteer was initially presented with a large latency in the range of 120–150ms. This latency was gradually decreased in 15ms steps until the volunteer reported that the latency could no longer be perceived. This value l_{high} is noted, and the experiment re-started with an initial low latency in the range of 0–30 ms. This value was gradually increased in 15ms steps until the volunteer reported being able to perceive the latency. The second value, l_{low}, was also recorded. The entire experiment was repeated 3 times, each time the initial high and low latency was randomly chosen.

3 Results

3.1 Haptic Recall Experiment Results

For each volunteer, the mean μ and standard deviation σ of FG_p were computed. μ indicates the volunteer's selection of needle resistance consistent with the sim-

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ulated procedure. σ indicates the consistency of the user's response. The former is dependent on the volunteer's assumptions of the needle-insertion procedure being simulated, the latter depends on the user's recall and ability to detect variations in haptic feedback. From Weber's law [21], we define the metric $W = \frac{\sigma}{\mu}$, which normalizes the volunteer's consistency over the individual's chosen needle resistance level. A small value for W indicates that the volunteer is consistently able to reproduce the same level of haptic feedback. A large W indicates poor consistency. Assuming a normal distribution of W over the population, we find $W_\mu = 0.20$ and $W_\sigma = 0.08$, where W_μ and W_σ are the mean and standard deviation of W respectively.

Figure 3 is a scatterplot of W against the volunteer's experience. It suggests that there can be a wide range in the subject's ability to consistently recall haptic events. For example, 14% of the volunteers had W values that were significantly higher than the rest of the group. In addition, it appears that haptic recall ability is not correlated with experience. Applying Pearson's correlation for the sample reveals a lambda coefficient of -0.17.

3.2 Latency Experiment Results

For each volunteer, the recorded values of l_{high} and l_{low} were averaged to determine the mean latency l_μ. For all volunteers, the mean and standard deviation of l_μ were 98ms and 19ms respectively. Assuming a normal distribution, Table 1 shows the cumulative distribution for selected percentiles. For example, the table indicates that 99% of the population are insensitive to a latency of up to 54 ms between visual and haptic feedback.

4 Discussion

Our experiment suggests that haptic recall consistency can vary widely among individuals. Moreover, this ability is independent of experience. This finding suggests that the method of using 'expert' opinion to fine-tune haptic feedback in surgical simulators may be unreliable, as it depends on the expert's ability to accurately recall haptic events. Greater accuracy can be achieved with accurate tissue measurements and better deformable models. While our experiment provides some insight on human haptic recall ability, shortcomings exist. For example, the metric W permits the comparison of consistency between subjects, but does not provide an absolute measure. Further work using a more refined metric is necessary.

Our findings also suggest that an appreciable fraction of the test population cannot detect a latency of 54ms or less between visual and haptic feedback. This result has significant implications. Adaptive algorithms can use the additional time to refine haptic feedback, allowing simulations to achieve better realism without sacrificing performance. Some network delays in a distributed surgical simulation environment may not be noticeable.

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Additional work is necessary to determine whether similar latency thresholds exist for more complex surgical tasks, such as suturing, cauterization, or dissection. In addition, further research is necessary to determine whether this latency is affected by the type of haptic device used. The CathSim® AccuTouch device uses a magnetic brake to generate a variable resistance to insertion and extraction. Realistic haptic responses can be simulated at graphics update rates (i.e., around 30Hz) . In contrast, force-reflecting devices such as the PHANToM use servo-motors to generate reaction forces. Considerably higher update rates are required. Additional experiments must be conducted to determine whether a similar latency is present.

5 Conclusion

This paper investigated the human perception of haptics, specifically the accuracy of haptic recall and sensitivity to haptic latency. Results from the haptic recall experiment suggest that the ability consistently recall haptic experiences varies significantly among individuals, and is independent of experience. Results of the latency experiment suggest most humans are incapable of detecting significant (54ms) haptic latency. While these are intriguing results, further study is required to determine whether the findings are generalizable to a wide range of simulations and haptic feedback devices.

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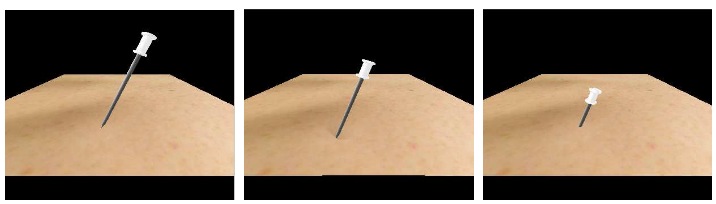
percentile	latency (ms)
90	74
95	67
98	59
99	54

Table 1. A cumulative latency table for the haptic latency experiment. Most humans (99%) seem incapable of detecting significant (54ms) haptic latency.

Fig. 1. CathSim® AccuTouch haptic interface



(a) (b) (c)

Fig. 2. Skin deformation during needle insertion. A

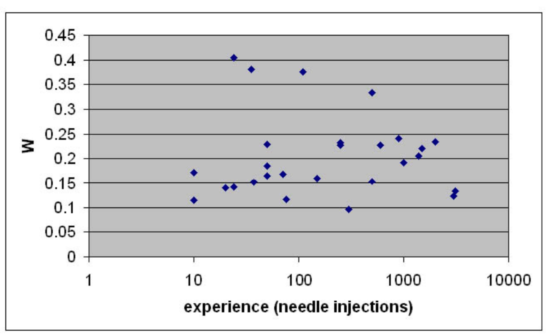


Fig. 3. A scatter plot with the consistency metric W plotted against the number of injections. Consistency varies widely among individuals, and seems independent of experience.