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Perceptual Rendering for Learning Haptic Skills

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Abstract

We approach the problem of creating haptic simulators that effectively impart skill without requiring high-fidelity devices by identifying perceptually salient events that signal transitions in the interaction. By augmenting these events, we seek to overcome deficiencies in the fidelity of the rendering hardware.

We present an extension of event-based haptic rendering to non-collision events, and we describe a user-study of the training effectiveness of passive force-field haptic simulation vs. active event-augmented simulation in a tool-manipulation task. The results indicate that active augmentation improves skill transfer without requiring an increase in the quality of the rendering device.

1 Introduction

We address the question of whether haptic skills can be effectively learned from renderings on low fidelity haptic devices. There has been considerable research on rendering specific haptic features or events (which we review below) but relatively little is known about rendering complex tasks that require skilled performance and training. Ideally we would like skilled performance of a real world task to improve after training on a virtual task with a haptic device.

One way to achieve effective skill transfer is to focus, not on the raw sensory data, but rather, on the sequences of perceptual events that occur during task performance. There is some evidence that the raw sensory information is not experienced directly but is quickly integrated into perceptual features that separate small "action phases" [4]. Even in the simple skill of lifting an object, the task involves approach, making contact, preloading grip forces, and lift off. Transitions between phases in the sequence are made based on the sensory signals. In this case, the primary role of sensory signals is event detection, that is, marking the start the next action phase and the corresponding changes in neural control.

A more complex skill on which we focus in this paper is inspired by a surgical procedure: bone-pin placement. In this surgical procedure, the surgeon stabilizes a fractured long bone by screwing a sharpened metal pin through the bone. This involves driving the pin through the hard outer cortex of the bone, then through through the spongy cancellous bone, then through the far cortical layer. Throughout these material transitions, the surgeon must maintain a controlled movement of the pin along its trajectory so as to avoid damage to the bone or soft tissue.

We hypothesize that over the course of such a procedure, there are specific events that are most perceptually significant when learning how to successfully perform the procedure. If these events can be identified, then the simulation can be designed to focus on rendering these events with high fidelity, without necessarily requiring that the entire simulation provide that level of fidelity. Such a focus could allow a simulation to be an effective trainer without requiring high-cost hardware.

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Related Work

There has been considerable work on the perception and rendering of haptic features. We broadly classify these features into two categories: *object features* and *interaction features*. Object features include shape [14], texture (which we take to include both friction and roughness [10, 8]) and elasticity [16]. Interaction features include making and breaking contact, and relative motion of the contact surface (including sliding, rolling, and sticking). Even though much of the existing literature on haptic perception (e.g.,[17, 1]) does not make a clear distinction between the two categories, there is evidence that these are used in very different ways in skilled human performance [4].

Event-based haptic rendering is one approach that focuses on the simulation fidelity of particular events. Salcudean and Vlaar found that a braking force pulse increases the perceived stiffness of a virtual surface upon penetration [15]. Constantinescu et al. extended this braking force approach to create impulsive forces in response to multi-body collision events [2]. A primary obstacle to haptic rendering focusing on discrete events is that traditional closed-loop controllers often do not operate at the high frequencies (up to 1 kHz) that mediate human perception of discrete events. By using brief open-loop high-frequency playback, triggered by contact events, Hwang et al. were able to reduce stopping distance and increase the effective stiffness of virtual surfaces [3].

The majority of research into event-based haptic feedback focuses on increasing the fidelity of stiff surface tapping. The effectiveness of event-based feedback has been gauged both by measurement of quantifiable properties (effective stiffness, rate-hardness, stopping distance) [3], and by single-blind studies of user ratings of realism [7, 12].

Finally, haptic interaction involves contact, which produces correlated sounds and visual deformation in addition to forces. Multisensory rendering of these contact events is therefore important; see [13] for a review.

One approach to the problem of skill transfer in manual tasks that goes beyond the straight-forward maximization of fidelity is the focus on differentiation of perceptual invariants [9]. In this model, the emphasis is on developing the trainee's sensitivity to changes in relationships between variables in the environment, in particular, those relationships that are invariant throughout successful execution of the task. Our approach is similar, in that we are exploiting the fact that skill transfer can be improved by controlled deviation from task similarity [18], and that we are seeking to identify features of a task that are most perceptually significant for skill transfer. The focus on perceptually pertinent events is also complementary to a focus on perceptual invariants; where the latter seeks to sensitize the trainee to perceptual phenomena that occur during each phase of a task, the former seeks to increase sensitivity to the events that signal transitions between phases.

Our Contributions

In the work presented here, we investigate event-based feedback corresponding to non-collision events, and we gauge the effectiveness of the event-based approach by its impact on learned task performance.

We conducted a user-study to investigate the effectiveness of event-based augmentation for simulator training. We developed a

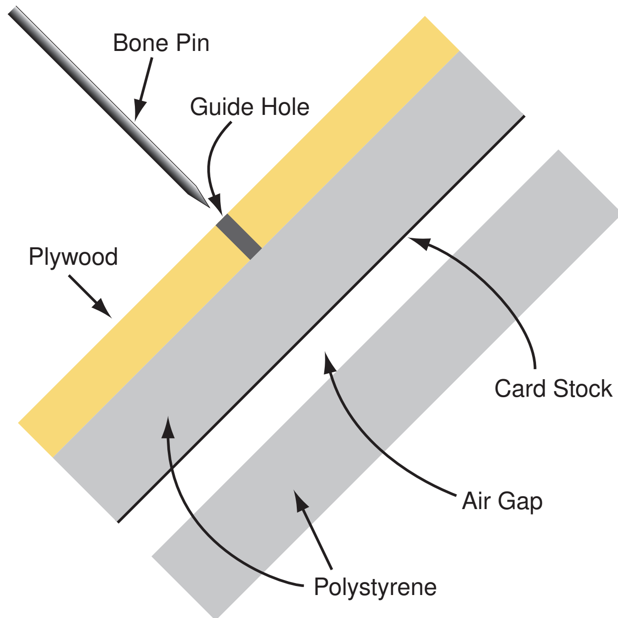
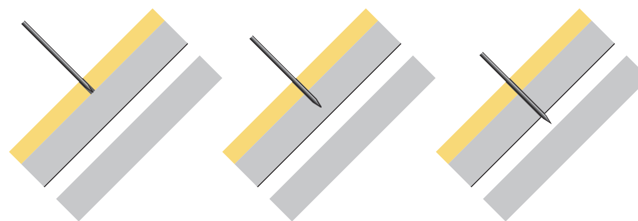


Figure 1: Experimental task setup (0.5 scale). A slab of polystyrene is laminated with card stock and separated from a second slab by an air gap. The pin's direction of movement is guided by a drill-hole through the covering plywood layer.



(a) Start (b) Carving (c) Complete

Figure 2: Task Procedure. (a) The task starts with the tip of the pin resting on the surface of the polystyrene. (b) The subject must drive the sharpened pin through the first polystyrene slab. (c) The subject must stop before the pin touches the second slab.

task that mimics the characteristics of the real-world surgical task of bone-pin placement. We compared the training effectiveness of passive closed-loop and event-augmented haptic simulations of this surrogate task. Our results showed that perceptual augmentation of a low fidelity haptic rendering produced measurable improvements in skill transfer.

The remainder of this paper is organized as follows. In Section 2 we describe the methodology of our user-study. The results of the study are presented in Section 3. In Section 4 we draw conclusions about the effectiveness of event-based simulator augmentation in training for surgical tasks.

2 Methods and Materials

This section describes the methodology of our user-study. Section 2.1 describes the task the subjects were required to perform, Section 2.2 describes the design and implementation of the simulators used by the subjects to train for the task, and Section 2.3 describes our experimental procedure.

2.1 Task

The task we developed for this experiment is a surrogate for the more complex task of bone-pin placement. Our experimental task focuses on the requirement that the pin must be inserted with sufficient control to prevent excessive motion of the pin when the resistance changes as a result of a transition from one material to another. The user's task was to drive a bone-pin (3 mm in diameter with a sharpened tip) through a slab of polystyrene (a surrogate for cortical bone) until the pin's tip emerged into an air gap (whose lower resistance parallels the low density and low strength of cancellous bone) on the far side of the slab (see Figure 1).

The polystyrene slab was 24 mm thick, and its far side was laminated with card stock to increase the force required to puncture through to the air gap behind the slab. The air gap was 13 mm thick; beyond it lay another slab of of polystyrene. Both slabs were mounted behind a layer of plywood; a guide hole was drilled through the plywood to govern the pin's insertion location and direction of motion. The entire assembly was arranged at a 45 °angle 0.9 m above the ground.

Since our haptic rendering hardware did not support the generation of torque about the axis of insertion, we removed the screwing component of the pin insertion - the pin was pushed through the polystyrene without a screwing motion (this is possible because the polystyrene slab is weaker than cancellous bone).

To successfully complete the task, the subject was required to push the bone pin through the first polystyrene slab, but stop before the tip of the pin reached the second slab (see Figure 2). The subject was also required to complete this insertion within 3 seconds (starting with the pin inserted through the guide hole with its tip resting on the surface of the first slab). The subject held the bone pin in a T-handled pin vise (see Figure 3a).

2.2 Simulator Design

To create a virtual model of the task apparatus, the real task's mechanics were measured by performing the task with an instrumented version of the bone-pin holder. The instrumented holder used an ATI Nano17 6-axis force/torque sensor and a VICON motion tracking system to simultaneously record the position of the pin's tip and the forces exerted on the pin (see Figure 3b). These recordings were used to guide the design of a haptic simulation whose force characteristics paralleled those of the real materials.

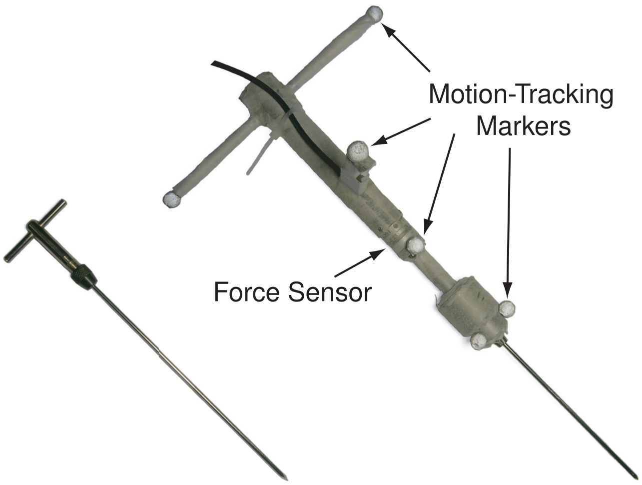
Analysis of the force/position profile showed that the force required to penetrate the polystyrene rose approximately quadratically with penetration depth, and that non-penetrating movement (i.e. movement that did not alter the structure of the material) was resisted by a force that was approximately linear with penetration depth.

We implemented our haptic simulation using a dynamic proxy whose behaviour is similar to that described by Mitra et al. [11]. The tip of the bone-pin is represented by a proxy, whose position, x_p, was coupled to a user-controlled master, x_m. The proxy's motion is constrained to one dimension (representing the movement of the bone-pin's tip along the axis of insertion).

We model the slab of polystyrene as an interval ($slab_{top}$ to $slab_{bottom}$ along this single dimension; for convenience, and w.l.o.g., we set $slab_{top} = 0$, $slab_{bottom} = -slab_{thickness}$. As the user inserts the bone-pin into the polystyrene, the structure of the environment is changed - a channel has been carved down to the point of maximum penetration. To model this dynamic aspect of the environment, we define a variable, $slab_{top} \geq x_c \geq slab_{bottom}$, representing the maximum depth to which the proxy has carved.

The position of the master can be described by one of three cases:

Non-Contact: when $x_m > slab_{top}$, the master (and the proxy) is not in contact with the slab.



(a) Bone Pin Holder (b) Instrumented Holder

Figure 3: (a) The bone pin is held in a T-handled pin vise. (b) To measure the force characteristics of the task, a pin holder was built that incorporated a force sensor and motion-tracking markers

Contact: when $slab_{top} \geq x_m \geq x_c$, the master (along with the proxy) is inside the slab, but not penetrating beyond the maximum depth carved so far.

Penetration: when $x_m < x_c$, the master is penetrating the virtual surface. Note that when $x_c = slab_{bottom}$ (i.e. the pin has carved all the way through the slab) the proxy is no longer in the **Penetration** case - it is handled by the **Contact** case.

We will describe the dynamics of our simulation separately for each of these cases. Note that we structure our dynamics so that the behaviour of our system is continuous across the case boundaries.

In the **Non-Contact** case, the proxy moves with the master, and no forces are generated:

$$\begin{aligned} x_p &= x_m && (1) \\ F_m &= 0 && (2) \end{aligned}$$

In the **Contact** case, to mimic the measured linear increase in resistance with pin depth, we damp the motion of the proxy with a factor that increases linearly with depth:

$$\begin{aligned} \Delta x_p &= (1-\alpha)^{\dagger}(x_m - x_p) && (3) \\ \alpha &= \alpha_{max}\frac{slab_{top} - x_p}{slab_{thickness}} && (4) \end{aligned}$$

where α_{max} is the maximum amount of damping (between 0 and 1) that occurs when $x_p \leq slab_{bottom}$ (to match our measured forces, we used the value $\alpha_{max} = 0.9$ for our update rate of 1 kHz). The force generated at the master is based on a spring coupling between the proxy and the master:

$$F_m = k(x_p - x_m) \qquad (5)$$

In the **Penetration** case, we build on the traditional dynamics for stiff surfaces, where the proxy stays on the virtual surface and exerts a force on the master:

$$F_m = \begin{cases} -kx_m, & x_m < 0 \\ 0, & x_m \geq 0 \end{cases} \qquad (6)$$

$$x_p = \begin{cases} 0, & x_m < 0 \\ x_m, & x_m \geq 0 \end{cases} \qquad (7)$$

† Corrections to the originally published paper are noted in red.

In this paradigm, the proxy can also be considered to be applying a force $F_p = -F_m$ on the virtual surface. In our model, the position of the virtual surface is dynamic, so we compute the force applied to the virtual surface as:

$$F_p = k(x_c - x_m) \qquad (8)$$

Unlike the traditional stiff surface, our surface must yield to allow the proxy to be moved deeper and deeper into the slab. However there is some minimum force that the surface is able to resist without its structure changing. Furthermore, our measurements showed that this minimum force should increase quadratically with depth. We define a quantity that specifies what force can be exerted on the surface without carving for a given value of x_c:

$$F_{resist} = a_0 + a_1 x_c + a_2 x_c^2 \qquad (9)$$

(fitting to our measured forces yielded $a_0 = 0.9$ N, $a_1 = -9.6$ N/m, $a_2 = 184.9$ N/m^2 for our material). If this threshold is exceeded ($F_p > F_{resist}$), then the proxy has carved the surface, and x_c must be adjusted. The carving should not move past the master position, and the amount of carving should be proportional to the force applied. We compute the new value of x_c to satisfy these conditions:

$$\begin{aligned} \Delta x_c &= \beta(x_m - x_c) && (10) \\ \beta &= \min(1, \gamma(F_p - F_{resist})) && (11) \end{aligned}$$

where γ is a tuneable parameter to control the rate of carving (all of our simulations used $\gamma = 10$ N^{-1}).

Since the value of x_c has been adjusted, the proxy is no longer fixed at its old position. We move the proxy to the new position of the surface, and use the new position to compute the master force:

$$\begin{aligned} x_p &= x_c && (12) \\ F_m &= k(x_p - x_m) && (13) \end{aligned}$$

The simulation was implemented using a dual 2.0 GHz Xeon workstation with 1 GB of RAM, and a SensAble Technologies PHANTOM haptic device with 6 degrees of freedom in position input and 3 degrees of freedom in force output. The same T-handled pin vise used in the real task was attached to the PHANTOM stylus so that it could be grasped in the same way as when performing the real task. The position of the PHANTOM stylus tip was the master for the simulation dynamics.

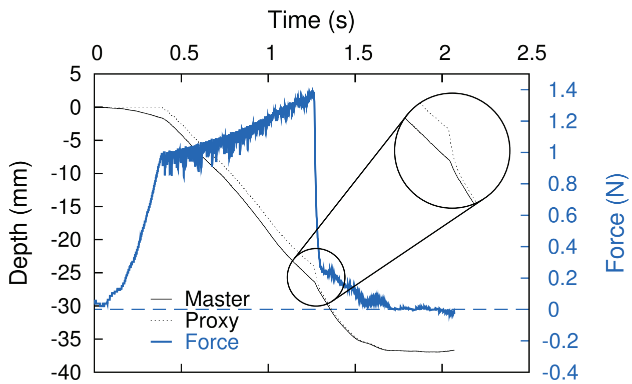
Using the above simulation model, three different versions of the simulator were created: full stiffness, degraded stiffness, and event-augmented degraded stiffness.

2.2.1 Full Stiffness Simulator

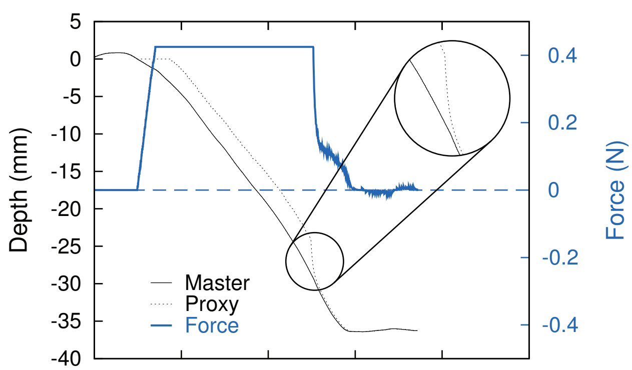
The baseline simulator used the PHANTOM device's maximum rated stiffness (600 N/m) and force output ceiling (8.5 N) to determine the virtual spring force k (between the master and the proxy) that was rendered to the user. The force/motion profile for an execution of the task on the full stiffness simulator is shown in Figure 4a. With this simulator, the force output is sufficient to allow the user's force to build up to F_{resist} before the movement of the virtual floor drops the resistance. Repetitions of this stick-slip type of behaviour yields high frequency variation in the applied force as carving occurs; this variation mimics the characteristics of the real material as the internal structure of the polystyrene breaks in discrete steps. This simulator also produces a noticeable discontinuity in the velocity of the master at the point of penetration.

2.2.2 Degraded Stiffness Simulator

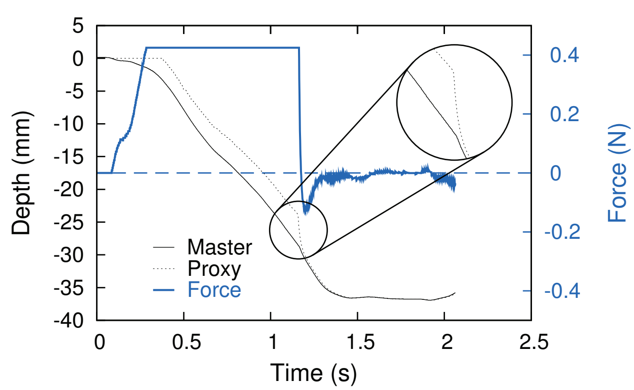
The degraded simulator artificially imposed lower stiffness (300 N/m) and force output ceilings (0.425 N) on the rendered



(a) Full Stiffness



(b) Degraded Stiffness



(c) Augmented Low Stiffness

Figure 4: Force/motion profiles for the different simulators. (a) The full stiffness simulator reproduces both the high-frequency force discontinuities encountered during carving, and the sudden negative acceleration of the master upon emergence from the material. (b) The degraded stiffness simulator saturates below the force levels at which high-frequency discontinuities occur and fails to generate significant master acceleration at the point of emergence. (c) The open-loop force pulse applied in the augmented low stiffness simulator restores some of the master acceleration at the time of emergence from the material.

force. The force was degraded only along the direction of penetration (the device's full capabilities were used to constrain the user's motion to the penetration channel). The force/motion profile for an execution of the task on the degraded stiffness simulator is shown in Figure 4b. The cap on this simulator's force output results in saturation that eliminates the high-frequency force discontinuities during carving, and the degraded stiffness severely reduces the velocity discontinuity of the master as it emerges from the virtual slab.

2.2.3 Augmented Low Stiffness Simulator

The augmented simulator used the same artificially lowered force parameters as the degraded simulator, but overlayed an open-loop event-based force pulse to exaggerate the emergence of the probe tip from the material. Event-based haptic rendering has primarily focused on creating high-frequency accelerations on impact with a stiff virtual surface; in this context, researchers have used hand-tuned decaying sinusoids and fixed-magnitude or fixed-duration pulses [2, 3, 15], as well as analytical acceleration matching transients based on measurements of real collisions [6]. The event that we are attempting to augment, however, is more like the stick-slip transition than stiff contact. This event is characterized less by the high-frequency ringing transients that result from rigid collision, and more by a sudden drop in resistive force and a corresponding increase in acceleration.

Since we have degraded the stiffness and maximum force of the passive component of the simulation, the drop in force upon emergence from the virtual material is less severe (and less perceptually noticeable). However, we can exaggerate the force change by applying a negative pulse (pulling the proxy further into the air gap); such a pulse has the effect of increasing the master's acceleration, requiring user compensation similar to that required by a higher-stiffness transition.

Rather than using a fixed-magnitude pulse, we use a decaying pulse, because while we want a sudden onset (corresponding to the sudden emergence of the pin tip from the material), the offset should be smooth (as the user adjusts the force applied to the master to lower its velocity). Similarly, we chose not to use a decaying sinusoid because the interaction does not call for high-frequency vibration upon emergence.

The pulse is initiated as soon as the proxy point moves below the deepest level of the material, and decays exponentially in time.

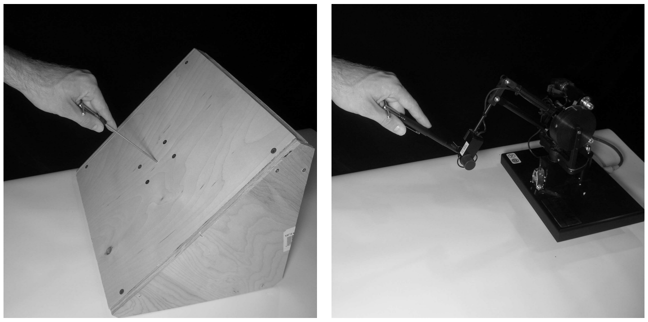
$$F_{pulse} = (-0.425\ \mathrm{N})(0.99)^{1000t} \tag{14}$$

The rendered force is capped at ± 0.425 N *after* summing the event-based pulse with the closed-loop spring force. The force/motion profile for an execution of the task on the augmented simulator is shown in Figure 4c. Although this simulator's force ceiling still eliminates the stick-slip behaviour during carving, the overlayed negative force pulse restores some of the velocity discontinuity at the transition into the air gap.

2.3 Experimental Procedure

18 subjects, recruited from faculty, staff, students, and visitors in the Rutgers Computer Science and Psychology departments, were included in the experiment. All subjects gave written consent and were compensated for their time (with money or course credit). There were two left-handed subjects (who performed the task and training with their left hands). The subjects were informed as to the purpose of the study (to gauge the effectiveness of different simulators on task performance), but were naïve as to the details of the simulation used. Each subject was randomly assigned to one of three groups corresponding to the three different simulators.

Prior to beginning the experiment, the subjects were told what the evaluation task was (including the material dimensions and the criteria for successful completion), but they were not able to see the



(a) Task Apparatus (b) Simulator

Figure 5: (a) The user cannot see the material inside the box, and must rely on haptic cues to complete the task. (b) The task is simulated using a PHANTOM device.

arrangement of the materials (which were concealed behind the top layer of plywood).

2.3.1 Baseline Phase

Before training, the subject performed multiple repetitions of the task (in most cases, 10). The pin was pre-positioned in the guide hole with the tip resting on the surface of the polystyrene slab. The subject was instructed to grasp the handle, push the pin through the polystyrene slab, and then release the handle without withdrawing the pin (see Figure 5a). After each repetition, the investigator informed the subject whether the pin was successfully inserted (fully penetrating the first slab without touching the second slab).

2.3.2 Training Phase

After performing the real task, the subjects were instructed on the use of the PHANTOM device and operation of the simulator (see Figure 5b). Each subject was allowed to train on the simulator for a total of 10 minutes (in two 5 minute sessions interrupted by a 1 minute break). During training, the subject could re-initialize the simulator as many times as desired and experiment with the simulation's dynamics in any fashion.

To provide high-level feedback to the user about successful completion of the task, the system emitted audible cues to signal whether the task was completed successfully or if the task was failed due to penetrating too far (past the air gap) or due to time-limit expiry.

The subjects were supervised during training, and the experimenter controlled the emergency shut-off switch for the PHANTOM.

2.3.3 Evaluation Phase

After completing the training phase, each subject was re-evaluated on the real-world task. The task conditions and instructions were the same as in the baseline phase of the experiment.

3 Results and Discussion

For each subject, we measured separately the rate of successful task execution before and after simulator training.

$$\text{success rate} = \frac{\text{successful executions}}{\text{total executions}} \tag{15}$$

$$0 \leq \text{success rate} \leq 1 \tag{16}$$

We compared the success rate before and after simulator training to determine the subject's absolute improvement.

$$\text{improvement} = \text{success rate}_{after} - \text{success rate}_{before} \tag{17}$$

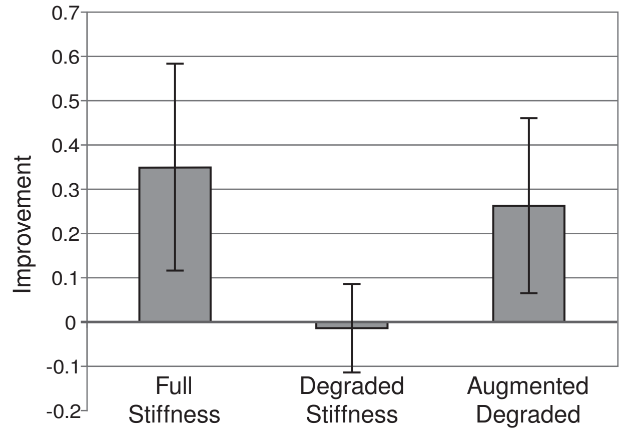


Figure 6: Task improvement by group. The mean change in success rate (and standard deviation) is shown for each simulator group.

$$-1 \leq \text{improvement} \leq 1 \tag{18}$$

The average improvements for each group of subjects are shown in Figure 6. The group that trained on the full stiffness simulator had an average improvement of 0.35 (σ = 0.23), the group that trained on the artificially degraded simulator had an average improvement of -0.01 (σ = 0.10), and the group that trained on our event-augmented version of the degraded simulator had an average improvement of 0.26 (σ = 0.20).

To interpret these results, we performed a two-sample Kolmogorov-Smirnov test on each pair of groups to test the null hypothesis in each case that the samples were drawn from the same underlying continuous distribution (i.e. that the type of simulator used did not differentiate the subjects with respect to task performance). The asymptotic p-values were 0.012 for the full stiffness group vs. the degraded stiffness group, 0.077 for the augmented group vs. the degraded stiffness group, and 0.81 for the full stiffness group vs. the augmented group[1].

The results presented in Figure 6 support our hypothesis that the event-augmented version of the degraded simulator is more effective at instilling reproducible skill than the degraded simulator's passive force-field alone.

These results also support the underlying assumption that the fidelity of a haptic simulation contributes to its effectiveness at imparting transferrable motor-skills (in that the group that trained on the un-augmented lower fidelity simulation showed little or no improvement).

4 Conclusions and Future Work

We have described a user study that showed that augmentation of events that signal perceptual transitions in a task can improve the training effectiveness of a simulator without requiring an improvement in the rendering capabilities (or increase in cost) of the simulator hardware.

In our future work, we intend to investigate the training effectiveness of event-based augmentation in other tool-manipulation tasks. Currently, we have only incorporated augmentation that provides feedback directly to the motor system; in line with our hypothesis that events can carry high-level information about the transition between phases of a task, we will investigate the effect of not only open-loop haptic augmentation, but also of multimodal perceptual cues (such as the use of audio signals to amplify the user's perception of significant haptic events).

[1] For a discussion of the accuracy of the K-S test's asymptotic p-values for small sample sizes, see Klotz, 1967 [5]

We also plan to explore a method for automatically identifying the perceptually salient events in the performance of a task, so that the choice of events to augment (and how to augment them) is simplified when designing a simulator for the task.

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