Spatially Separated Cutaneous Haptic Guidance for Training of a Virtual Sensorimotor Task

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Abstract— **Haptic devices enable multi-modal feedback to a user when training to perform novel motor skills in controlled, virtual environments. Haptic feedback has been proposed as a means to provide additional guidance cues that might improve training efficacy; however, recent studies have identified drawbacks to haptic guidance, including reliance on guidance forces and an inability to distinguish between forces that are part of the virtual environment and those that communicate task completion strategies. Recently, we proposed a novel approach to providing haptic guidance that separates task and guidance forces. We used a kinesthetic haptic interface to communicate task forces and a spatially separated tactile skin-stretch device to transmit guidance forces. Our experiments showed that feedforward control using this paradigm was effective for improving performance in a trajectory following task. In this paper, we explore the potential for spatially separated cutaneous haptic guidance to train a user to optimally control an inverted pendulum system. We present and execute a task and training protocol designed to determine whether error-based haptic feedback provided cutaneously can accelerate learning of a task, and whether participants can retain or transfer task skills even after guidance is no longer present. We found that subject performance improved while spatially separated cutaneous haptic guidance was active. Despite this finding, performance in the pendulum balancing task was not affected once the haptic assistance was removed.**

I. Introduction

One of the most extensively studied applications of haptics is virtual training. Of the many allures of haptic training, the most frequently cited include leveraging the online programmability of haptic or robotic devices to augment and accelerate skill acquisition; the ability to train complex or risky real-world tasks in a controlled and safe environment; and the potential for a single human trainer to have a wider effect by training multiple individuals simultaneously or remotely. While a great deal of literature suggests that the addition of haptic cues improve performance of tasks in virtual environments [1]–[3], there is limited evidence that haptic training ultimately leads to enhanced skill retention once guidance is removed [4]. One possible explanation for this phenomenon lies in the difficulty of delivering different types of haptic training forces simultaneously to trainees [5].

Haptic training forces can primarily be categorized as *task forces* or *guidance forces* [6]. Task forces are generally associated with the simulated dynamics and/or collisions of a virtual environment, and are usually meant to provide the user with a plausible representation of an otherwise real-world task. Guidance forces are supplemental forces which may inform users of how a task should be completed,

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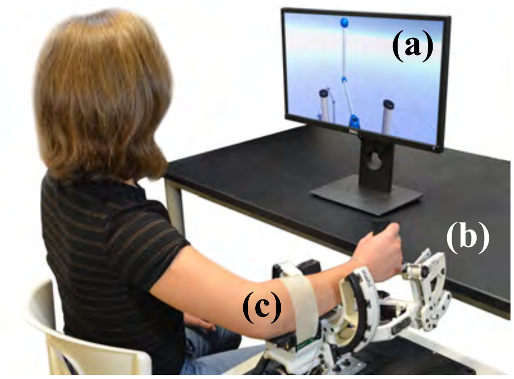

Fig. 1. A subject learns to balance a **(a)** virtual pendulum haptically rendered by a **(b)** kinesthetic haptic device on the hand while task training is administered through a **(c)** cutaneous haptic device worn on the forearm.

and may even provide assistance. A well known example of guidance forces is the concept of virtual fixtures [1], which deliver convergent forces along a desired trajectory. Shared control is yet another example, where a virtual "expert" assists trainees [7]. It is also worth mentioning another approach to haptic guidance for training is known as error augmentation, an approach that provides forces that exaggerate user error [8].

When multiple sources of force are rendered through the same haptic interface, users easily confuse those associated with task dynamics with those meant to either convey completion strategies or augment the learning process [6]. As a result, haptic devices that separate the different types of forces across multiple points of contact have been proposed. This method is referred to as "spatially separated assistance," or SSA [6]. One of the major arguments for SSA is that it provides trainees with as much haptic information as possible, while allowing users to discern task forces from guidance or disturbance forces [9]. SSA further offers the ability to make learning from haptic guidance less of a passive exercise, and more of an active one. If the guidance forces are sufficiently decoupled from input to the task device, trainees must actively interpret cues at one location, and translate them to another. Since active learning is generally considered to be better than passive [10], SSA may prove to be more efficient than other forms of haptic guidance for certain scenarios. To date, a large portion of research into SSA, and haptic guidance in general, has involved complex kinesthetic type haptic interfaces designed specifically for the task (e.g. rowing [11], [12], skiing [13], and tennis [14] training). A more generalized approach to SSA was proposed in [6], but still required two identical kinesthetic joysticks.

Therefore, simplified methods of providing SSA are desired.

Recently, we presented a novel form of SSA that combines traditional kinesthetic task devices with small, inexpensive cutaneous training devices [5], [15]. This approach was motivated by the advantages of cutaneous feedback over kinesthetic feedback, including the applicability to a wider variety of complex tasks and the ability to integrate closely with the human body [16], [17]. Cutaneous assistance via skin-stretch has been shown to help users perform planar hand movements [18], and tactile cueing has been found effective in guiding wrist movements [19]. Wearable devices have also been used in rehabilitation training [20] and as sensory augmentation for the those with vision or auditory loss [21].

In an experiment that evaluated our cutaenous-based SSA design, subjects were tasked with following an invisible trajectory using a kinesthetic task device with their dominant hand. Meanwhile, a cutaneous skin stretch device provided spatially-separated haptic guidance to users by stretching forearm skin in the direction they should move. Results showed that this multi-sensory approach to SSA effectively delivered haptic guidance to users under a feedforward skin-stretch paradigm, but the efficacy of feedback, or error-based, paradigms was inconclusive. Additionally, a major limitation of the experiment was that it did not allow for the testing of skill retention after cutaneous guidance was removed, since the task was found to be difficult to complete without guidance active. To fully evaluate the proposed cutaneous SSA system's viability as a haptic training platform, unanswered questions regarding its ability to train otherwise learnable tasks should be answered.

The objective of this paper is two-fold: (1) to assess the applicability of cutaneous-based SSA to motor learning tasks and skill retention, and (2) to reassess the use of feedback guidance, i.e. guidance which attempts to train users with error correcting strategies. We present a new task in which subjects are required to balance a virtual inverted pendulum (Fig 1a) through a *Kinesthetic Haptic Device* (Fig. 1b) providing haptic feedback of task forces. To assist subjects in learning the task, cutaneous training cues based on optimal control are provided through a *Cutaneous Training Device* (Fig 1c) worn on the ipsilateral arm. The task, devices used, and training paradigm are described in Section II. The experimental design is presented in Section III. Results are presented and discussed in Section IV with our conclusions following in Section V.

II. Task Design

This paper investigates the task of balancing an inverted pendulum (Fig. 2). Pendulum balancing requires the interpretation of visual and haptic information, understanding the state of the dynamic system, and quick reaction to correct the pendulum before it falls. Balasubramaniam investigated the skill of stick balancing and found that this ability can be learned and trained [22]. This task is therefore well suited to testing the efficacy of haptic guidance for a system where feedback (error-based) control is required. Because the pendulum dynamics react to the movement of the participant, feed-forward control is neither viable nor useful. This contrasts well with our previous work [5] that required subjects to follow a trajectory without visual cues that could not be intuitively learned without haptic guidance. The learnable nature of the pendulum balancing task makes it ideal for testing skill retention, since subjects should be able to complete the task once guidance is removed. The previous task design showed that subjects were effective with feed-forward assistance, but had a difficult time interpreting feedback guidance. Testing our cutaneous-based SSA for feedback guidance expands the range of applications where it can be used.

A. Pendulum Modeling and Simulation

The inverted "Furuta" pendulum was used in place of a translational pendulum-cart system in order to intuitively match the purely rotational *Kinesthetic Task Device*. The pendulum system is depicted in Fig. 2, and is simulated by numerically integrating equations

$$\begin{aligned}\tau_1 = [l_1^2 m_1 + (L_1^2 - l_2^2 c_2^2 + l_2^2) m_2 + I_{1,xx} + I_{2,xx} \\ -c_2^2(I_{2,xx} - I_{2,yy})]\ddot{\theta}_1 + b_1\dot{\theta}_1 - l_2 L_1 m_2 c_2 \ddot{\theta}_2 \\ +L_1 m_2 s_2 l_2 \dot{\theta}_2^2 + [m_2 l_2^2 + I_{2,xx} - I_{2,yy}] 2 s_2 c_2 \dot{\theta}_1 \dot{\theta}_2\end{aligned} \tag{1}$$

$$\begin{aligned}\tau_2 = -l_2 L_1 m_2 c_2 \ddot{\theta}_1 - s_2 c_2 (m_2 l_2^2 + I_{2,xx} - I_{2,yy})\dot{\theta}_1^2 \\ +(m_2 l_2^2 + I_{2,xx})\ddot{\theta}_2 + b_2\dot{\theta}_2 - l_2 m_2 s_2 g = 0\end{aligned} \tag{2}$$

where

$$m_1 = \pi L_1 r_{link}^2 \rho \tag{3}$$

$$m_2 = \pi r_{link}^2 l_2 \rho + \frac{4}{3}\pi r_{mass}^3 \rho \tag{4}$$

$$l_1 = \frac{L_1}{2} \tag{5}$$

$$l_2 = \frac{(3L_2^2 r_{link}^2 + 8 L_2 r_{mass}^3 + 8 r_{mass}^4)}{(6 L_2 r_{link}^2 + 8 r_{mass}^3)} \tag{6}$$

θ_1, θ_2, and their derivatives are the pendulum state, s_i is $\sin\theta_i$, c_i is $\cos\theta_i$, τ_1 and τ_2 are the pendulum joint torques The derivation of the inertial terms, $I_{1,xx}$, $I_{1,yy}$, $I_{2,xx}$, and $I_{2,yy}$ have been omitted for brevity, but can be computed by treating link 1 as a solid cylinder and link 2 as a combined solid cylinder and sphere. The pendulum is parameterized by a uniform density ρ, and radii r_{link} and r_{mass}.

B. Pendulum Balancing via the Kinesthetic Task Device

The task requires subjects to continuously balance the pendulum from an initial upright state of $\theta_1 = 0$, $\theta_2 = \epsilon$, $\dot{\theta}_1 = \dot{\theta}_2 = 0$, where ϵ is an arbitrarily small deviation from 0 so that the simulation is not initially stable. Subjects must use visual and haptic feedback to maintain an upright position.

As in [5] and [15], the OpenWrist [23] was chosen as the task completion device (Fig. 1.b). It is a 3DoF wrist exoskeleton with joints for forearm pronation/supination (PS), wrist flexion/extension (FE), and wrist radial/ulnar deviation (RU). Subjects rotated the FE joint for the task, while the other two joints were locked through control. While maintaining control of the first link, subjects could feel the pendulum reaction torque τ_1, which is rendered with the OpenWrist through a virtual coupling impedance

$$\tau_1 = K(\theta_{ow} - \theta) + B(\dot{\theta}_{ow} - \dot{\theta}) \quad (7)$$

where θ_{ow} and $\dot{\theta}_{ow}$ are the position and velocity of the OpenWrist FE joint. The spring constant K=25 Nm/rad and damping constant B=1 Nm-s/rad were chosen to make the impedance stiff yet stable.

The pendulum was constrained so that the first link could not rotate more than 50° in either direction. This constraint was implemented as a virtual wall rendered by the OpenWrist *Kinesthetic Task Device*, and was visually represented with two posts on either side of the virtual pendulum (Fig. 4). The simulation and robot control was implemented in C++ using the Mechatronics Engine and Library (MEL), while the visualization was created in Unity Engine.

Pendulum parameters were chosen so that subjects could sense the dynamics without becoming fatigued over the course of the experiment. Three variations of the pendulum were created by changing L_2, corresponding to an Easy, Medium, and Hard difficulty (Fig. 3). The order in which the variants appear is randomly chosen, but each is equally represented. The pendulum parameters are listed in Table I. The task is further complicated by the introduction of random forces on the ball. A random force noise, implemented as smooth Perlin noise, gradually increases in magnitude the longer the pendulum is balanced, making more extreme corrections necessary. The escalating random noise increases difficulty over time and stops any single trial from continuing indefinitely.

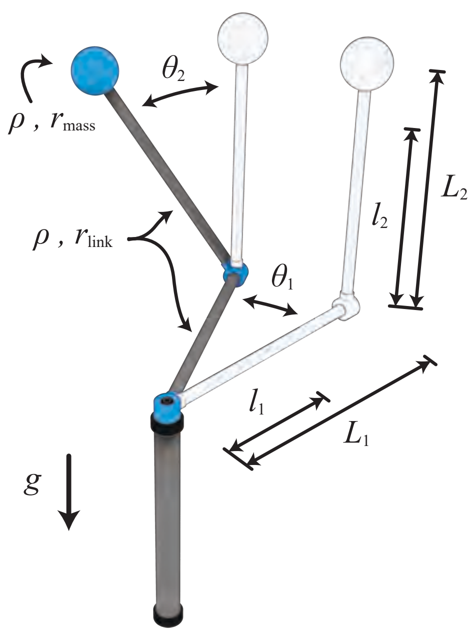

Fig. 2. An inverted "Furuta" pendulum was used for this work and has two rotational degrees of freedom, θ_1 and θ_2. Link 1 moves in the horizontal plane while the link 2 is constrained to rotate along the axis of the link 1. The mass at the end of link 2 increases the challenge of balancing.

Task performance is measured as the duration of sustained inversion, defined by maintaining the potential and kinetic energy of the system within stability-based thresholds. The current time score is represented through the color of the ball and joints, which fade through a predetermined color gradient for the duration of the inversion. The color change keeps subjects engaged and motivates them to "unlock" new colors, but avoids the distraction of numeric scores on screen. Each trial ends when the subject loses control and the pendulum energy falls outside the specified constraints.

C. Optimal Feedback via the Cutaneous Training Device

Spatially separated cutaneous assistance is delivered to participants through the *Cutaneous Training Device*, located on the ipsilateral forearm. The Clenching Upper-limb Force Feedback device (CUFF) [24] served this role. The device tightens a silicone-fabric band around the user's arm to distribute tactile forces against forearm skin (Fig. 1c). To help subjects develop intuition for the correct motion required to balance the pendulum, the device stretched the forearm skin circumferentially to convey the magnitude and direction the FE joint of the OpenWrist *Kinesthetic Task Device* should be moved.

The *Cutaneous Training Device* provided feedback-based guidance. First, an optimal Linear Quadratic Regulator (LQR) controller read the current pendulum state and computed the control torque $\tau_{1,LQR}$ that would force the pendulum upright if supplied directly to the system. The LQR controller was designed using the linearized forms of Eqs. 1 and 2 about the operating point $\theta_1 = \theta_2 = \dot{\theta}_1 = \dot{\theta}_2 = 0$. This optimal torque was then converted to the CUFF *Cutaneous Training Device* band rotation through the

TABLE I
PENDULUM PARAMETERS

Parameter(s)	Variant 1	Variant 2	Variant 3	Units
L_1	100	100	100	cm
L_2	140	100	50	cm
r_{link}	2.5	2.5	2.5	cm
r_{mass}	10	10	10	cm
b_1, b_2	0.01	0.01	0.01	Nms/rad
ρ	10	10	10	kg/m^3

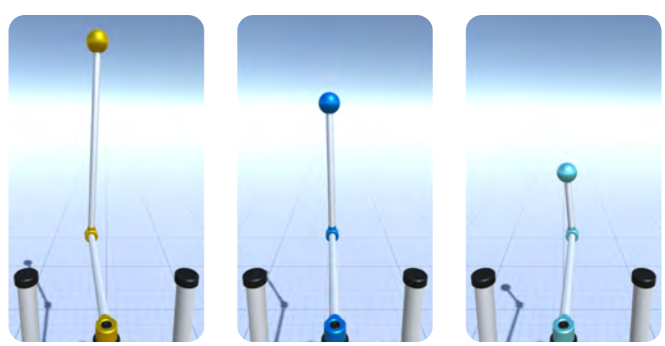

Fig. 3. The three pendulum variants presented to users. Shorter pendulums are more difficult to balance. Pendulum color changes over the course of a trial to give subjects an indication of their score and encourage progression.

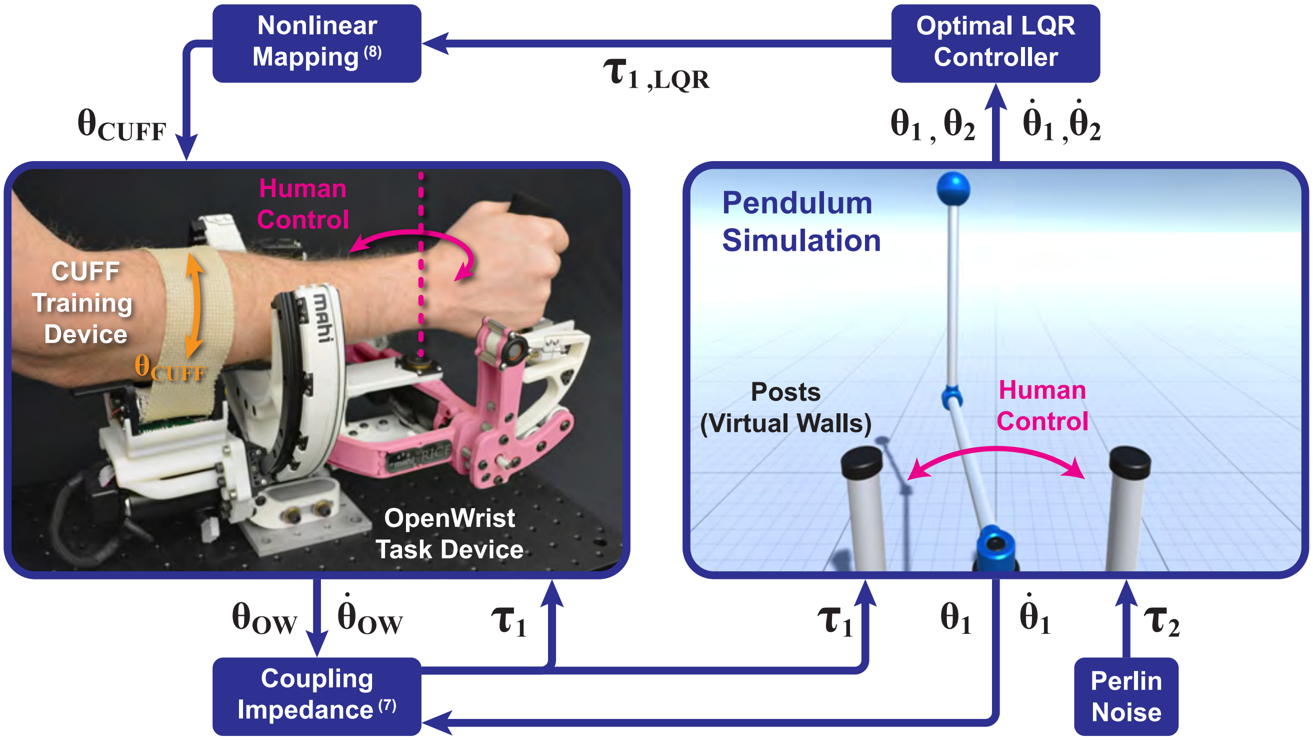

Fig. 4. Virtual Pendulum Simulation and Control Loop - The FE joint of the OpenWrist is coupled to the base joint of the pendulum. The coupling torque is rendered on the OpenWrist and applied to the virtual pendulum system. An optimal LQR controller computes the torque required to right the system then maps that torque to the angle of the CUFF device.

nonlinear logarithmic mapping given by the equation

$$\theta_{CUFF} = A \cdot \ln(B \cdot \tau_{1,LQR} + C) + D \quad (8)$$

where parameters A, B, C, D were consistent across all subjects and hand-tuned to asymptotically approach the CUFF hardware limit while having high gain at $\tau_{1,LQR} = 0$. In contrast to a linear scaling factor, this mapping allowed subjects to perceive feedback for small errors without encountering the position limit of the CUFF for large errors. If the subject balanced the pendulum perfectly, the LQR controller computed zero torque and the band remained at the zero position. Once the pendulum began to tilt, the control torque increased in magnitude and the band rotated, imparting a shear force on the subject's forearm. The complete control loop including human interaction is illustrated in Fig. 4.

III. Experiment Design and Analysis

Twenty student participants (15 male, 5 female, ages 20 to 27) were recruited and evenly divided across two experimental conditions. Each subject participated in a single session beginning with a 45 second familiarization period, followed by 7 evaluation blocks interleaved with 6 training blocks. Each block followed the same structure, in which the trials were divided evenly into easy, medium, and hard trials (Table I), and the order of the trials was randomly presented. Each evaluation block contained 6 trials, 2 for each difficulty, while each training block contained 36 trials, 12 trials for each difficulty. Because trials lasted for as long as the participant could balance the pendulum, a single subject session varied in length from 30 to 90 minutes total.

The procedure for both conditions was the same, with the sole difference being the presence of the *Cutaneous Training Device* feed-back during training blocks for the "Cuff" condition, and its absence for the "No Cuff" condition. Both groups received pendulum dynamics rendering via the *Kinesthetic Task Device*. No participant received cutaneous feedback for any evaluation trials, regardless of experimental condition. We did not include a condition without visual feedback because the resulting task would be prohibitively difficult.

We analyzed the performance of subjects based on the time they kept the pendulum balanced in each trial. Outlier removal was considered at the block level, segregated by difficulty. If a trial was found to have a score greater than 1.5 interquartile ranges outside of the 25th and 75th percentiles, its value (balance time) was replaced with the subject's mean balance time. A subject was omitted from analysis entirely if more than 50% of their total trials for any difficulty met this criteria. One subject in the "No Cuff" condition met this criteria and their data were removed prior to further analysis.

To test the effect of condition, block, and difficulty on subject performance, we ran a three way mixed ANOVA for training [2 Conditions x 6 Blocks x 3 Difficulties] and evaluation [2 Conditions x 7 Blocks x 3 Difficulties]. Although Levene's Test indicated that we could only assume homogeneity of variances in evaluation but not training, the robustness of the ANOVA for similar sample sizes led us to continue analysis. Sphericity violations, observed via Mauchly's test in both training and evaluation, were treated with a Huynh-Feldt adjustment.

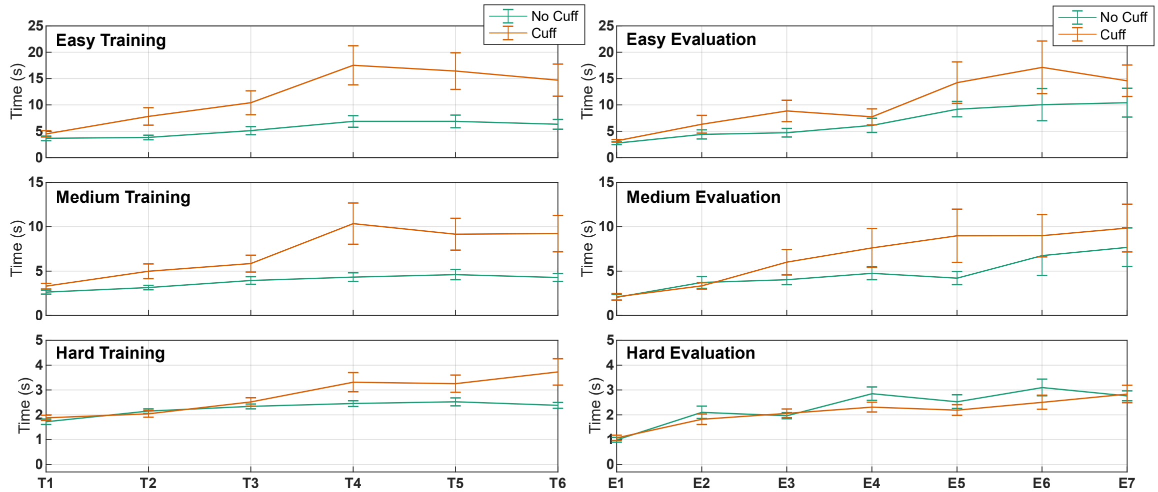

Fig. 5. Mean subject performance for each block and difficulty with error bars for ±1 standard error. Within training blocks, while the haptic guidance was still active, "Cuff" condition participants reached better times on average. Once the feedback was taken away for evaluation trials, the performance of the two groups is almost indistinguishable.

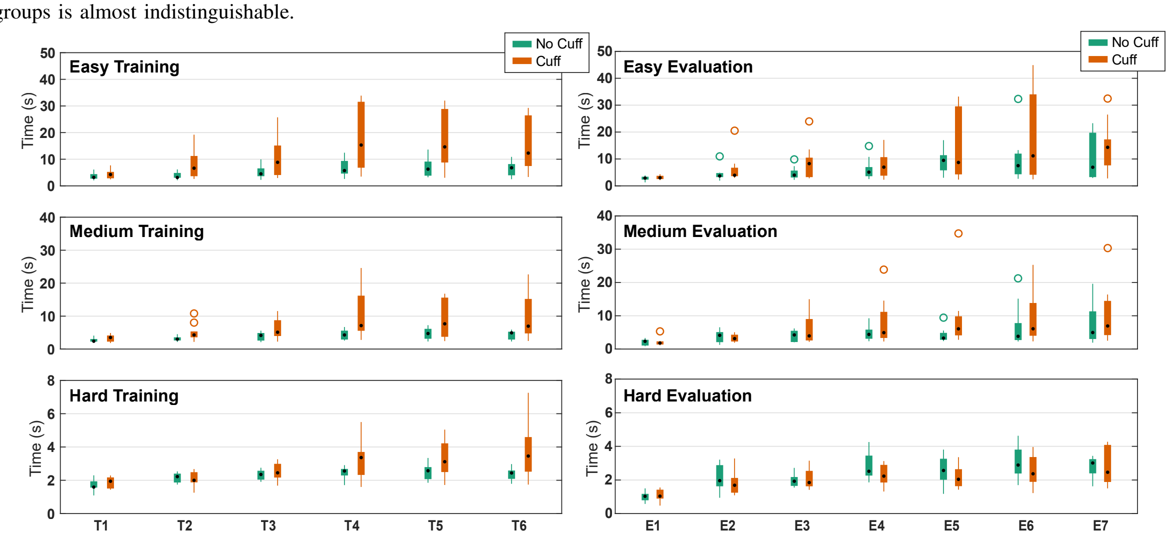

Fig. 6. Mean subject times for each block separated by difficulty. In training trials, the "Cuff" subjects varied in performance much more than the "No Cuff" subjects. Once the haptic guidance is removed during the evaluation trials, the distributions of the two condition groups look much more similar.

IV. Results and Discussion

Mean subject performance after outlier treatment is shown in Fig. 5, with error bars representing the standard error of the mean, for each block and difficulty. Fig. 6 is a boxplot of the same data.

Within training trials, results of the ANOVA show that there was a statistically significant main effect of condition ($F(1,17) = 6.178, p = .024$). There was also a statistically significant three-way interaction between condition, block, and difficulty ($F(2.6, 44.56) = 4.219, p = .013$). Subjects in both conditions improve during initial blocks then stagnate in performance, but Fig. 5 and a Welch t-test show that "Cuff" subjects reached a higher peak performance by T6 for easy ($t(10.64) = 2.63, p = .024$), medium ($t(9.84) = 2.36, p = .041$), and hard ($t(10.01) = 2.47, p = .033$) difficulties. The error bars in Fig. 5 and boxplot in Fig. 6 reveal the substantial increase in "Cuff" condition variability during later training blocks. Some subjects improved very little across the experiment, regardless of condition, creating a static lower bound. Highly skilled subjects, however, used the haptic guidance to push the upper bound of performance higher than subjects without guidance.

The evaluation trials tested retention of skills with guidance removed and found no significant difference between conditions. The ANOVA fails to show a significant main effect of condition ($F(1,17) = 1.348, p = .262$), and Fig. 5 shows only minor divergence between condition times. Since there were only two trials of each difficulty in each evaluation block, overall variability is larger for both conditions. "Cuff" subjects expressed frustration at having so few practice trials without haptic guidance, and their performance during evaluation dropped to the same level as the "No Cuff" subjects.

For most subjects, haptic guidance improved balance time while active, but did not affect performance once turned off. This work confirms that results of our prior experiment [5], that subject performance increases significantly with the introduction of cutaneous SSA. However, this task and training method proves that error-based feedback control using cutaneous SSA can be effective, contrasting the previous work where subjects with feedback guidance performed no better than those without. Once spatially separated assistance is removed, subjects return to the performance level of those without guidance. Despite some studies showing skill retention after haptic training [25], most fail to demonstrate retention once guidance is removed [26], [27], [4], [6], and our results continue this trend. Although this training paradigm did not result in improved performance after guidance was removed, the spatial separation of this assistance paradigm from the hand to the forearm means that guidance can still be administered during real-world tasks. The compact and inexpensive nature of the CUFF also bolsters its ability to be used for real tasks alongside other equipment.

V. Conclusion

To conclude, this paper has presented an experiment to test the ability of a combined kinesthetic-cutaneous SSA system to accelerate learning of a virtual task. The pendulum balancing task is designed to be learnable and require feedback control. Subjects completed the task and received task forces through the OpenWrist exoskeleton, while spatially separated cutaneous guidance forces were delivered through the CUFF device. We compared pendulum balancing performance of subjects that used this training method to those that trained without cutaneous guidance. Experimental results showed that haptic guidance improved mean subject performance during training trials where it was active, but the effect was not retained during evaluation trials, where the haptic guidance was no longer active. This study illustrates the efficacy of cutaneous error-based feedback control for a task where feed-forward control is not viable because the pendulum trajectory is not predetermined. Cutaneous SSA has the potential to be implemented in a wider variety of tasks now that its usefulness has been demonstrated both for pre-determined systems and those that react to user input.

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