Passive and Active Assistance for Human Performance of a Simulated Underactuated Dynamic Task

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Abstract

Machine-mediated training of dynamic task completion is typically implemented with passive intervention via virtual fixtures or active assist by means of record and replay strategies. During interaction with a real dynamic system however, the user relies on both visual and haptic feedback real-time in order to elicit desired motions. This work investigates human performance in a Fitts' type targeting task with an underactuated dynamic system. Performance, in terms of number of hits and between-target tap times, is measured while various passive and active control modes are displayed concurrently with the haptic feedback from the simulated system's own dynamic behavior. It is hypothesized that passive and active assist modes that are implemented during manipulation of simulated underactuated systems could be beneficial in rehabilitation applications. Results indicate that human performance can be improved significantly with the passive and active assist modes.

1 Introduction

Recently, virtual reality-based haptic training simulators have attracted the attention of a large number of researchers. The incorporation of haptic feedback in virtual reality simulations has been shown to further enhance learning rates, task performance quality, dexterity, and feelings of realism and presence over visual feedback alone [1-5]. Hence, acquisition of new motor skills might be expected to improve with the addition of haptic feedback in virtual reality based simulations. Studies, however, have shown mixed results for transfer of skill from the virtual to the real environment [5-10].

There have been relatively few studies to determine efficacy of haptic feedback in training. Yokokohji, et al. investigated skill transfer in haptic training using the "What You See Is What You Feel" type of display [6]. They proposed various methods for haptic training, but found no clear evidence of skill transfer for any of the proposed methods. Adams, et al. presented a study on the effectiveness of haptic training in a manual assembly task [5]. Although they found significant improvement in performance due to training, it was not clear if the improvements were attributable to the force feedback.

Several researchers have sought to use haptic devices as virtual teachers. In these instances, desired trajectories or interaction forces are programmed or recorded during an initial trial and played back to the subject in subsequent trials. These methods rely on a two-part training procedure. First, the subject is passive while the machine guides them to complete a desired motion or displays a desired force profile. Then, the machine is passive while the subject actively tries to replicate the performance. Henmi and Yoshikawa used this approach in a virtual calligraphy system [7]. Gillespie, et al. used the record and playback method to display the optimal trajectory for balancing an inverted pendulum attached to a 1-DOF cart in the shortest possible amount of time [8]. Their results were inconclusive, though it was noted that the subjects were encouraged to adopt an alternate strategy when exposed to the teaching mode. A similar strategy was used by Kikuuwe and Yoshikawa for motion/force teaching using a fingertip presser, with limited success [9]. They indicate that subjects learned to perceive the teacher's action's clearly but not accurately.

Many haptic training studies have also focused on the display of assistive cues, often referred to as virtual fixtures, for improved human performance of positioning tasks in virtual or remote environments with force feedback. For example, Rosenberg introduced the notion of virtual fixtures as perceptual overlays for enhanced operator performance in telemanipulation tasks [10]. Virtual fixtures have also been used to improve performance in refueling tasks [11] and for manipulation assistance during interactive tasks between humans and robots [12]. Mussa-Ivaldi has shown that the application of force fields via a haptic device can cause humans to adapt to the conditions and perform desired motions [13]. He was able to show that the effects were retained for some time. Feygin, et al. used haptic guidance for training users to follow complex 3D paths [14]. They found that while visual feedback was effective for teaching the trajectory shapes, haptic feedback influenced the learning of the temporal aspects of the task. Finally,

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Steele and Gillespie implementing a shared control strategy for a steering task for improved user performance during the steering task [15]. Their application, however, was not training since it was intended that the user would always use the shared control.

In this work, we investigate effects of haptic feedback on a user's ability to control underactuated dynamic systems. Dingwell et al. [16] have studied human control strategies for a spring-mass system that was constrained to move in one degree-of-freedom. They note that just as robots can be programmed to control unactuated joints, humans have the same ability. They were specifically interested in the methods that humans use to control these systems such as the formation of internal models or basing current performance tactics on prior experience. They determined that subjects learn to control the kinematics of manipulated objects via the formation of internal models. These models specify the forces that the subjects must exert on the object in order to induce the desired motions. We are interested to find if virtual assistive cues can improve human performance in a similar task as that used by Dingwell et al.

Control of flexible structures such as ropes or springs, or of systems of masses connected by flexible links, requires the user to control more degrees of freedom than the number of controllable inputs. Such tasks require processing of visual and haptic data for successful completion, and are candidate tasks for rehabilitation in the instance of impaired motor control, as is the case for stroke, Parkinson's, and spinal cord injury patients. For rehabilitation applications, the end goal is direct control of the system, either virtual or real, without intervention by a therapist or embedded control system. Therefore, we present a targeting task involving control of an underactuated system of two masses connected by a spring and damper in parallel. Three control modes were presented to subjects during the experiments. These were passive assistance, shared control, and a combination of assistance and shared control.

We wish to determine if human performance of a dynamic task with an underactuated system can be improved with the addition of passive and active virtual guides. This paper will present the results of a baseline study used to determine initial user performance of the task under several control conditions. We are primarily interested in the ability to train or rehabilitate subjects to perform dynamic tasks involving unactuated joints. Human performance studies were conducted for three control modes while healthy subjects performed a Fitts' tapping-type experiment [17] with a spring-mass-damper system. Results presented in this paper present a baseline of human performance for the Fitts'-type task. The effectiveness of each control mode as a training tool will be investigated in future work.

2 Theoretical Framework

In this section, we present arguments towards the selection of an underactuated spring-mass system as a test bed for our experiments. We provide the equations of motion of the system and use the coupled dynamics of the system to derive a controller for set point control of the underactuated end-effector, which is later used in the experiments. We also provide an analysis of important aspects of the controls problem from the human operator's view point and propose an active and a passive control paradigm for faster and more accurate user control of the positioning tasks.

2.1 The Underactuated System

In real life, human beings demonstrate the capability to control complex underactuated systems with appropriate training and practice. Typical examples include pole balancing, steering control of an automobile or stable control of a yo-yo. In performance of tasks, which are essentially dynamic in nature, haptic feedback is considered to play an important role [18]. Control of a yo-yo by the user is a good example of such a case, where temporary loss of visual feedback need not affect user performance after a certain period. Robotic control of a yo-yo can only be achieved through a nonlinear controller and has been proposed as an evaluation system for intelligent controllers [19]. Given the design simplicity of the yo-yo and associated complex dynamics, a similar virtual system was implemented for our experiments.

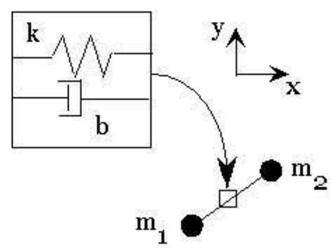

Figure 1. Virtual underactuated system. Inset shows the spring-damper model of the string connecting the point masses, m_1 and m_2.

2.1.1 System Description

The model of the underactuated system used in our study is shown in Figure 1. The system consists of two point masses connected by a flexible string modeled as a spring and a damper in parallel. The complete system was constrained to move in a plane, with no additional constraints. In the experiments described, users had complete control of the movement of one of the masses,

$\mathbf{m_1}$, whereas the movement of the mass $\mathbf{m_2}$ was determined solely by system dynamics. Thus, the resulting system had 4 degrees-of-freedom (DOF) with only two of them being controlled.

2.1.2 Dynamics and Control of the System

The equations of motion describing the dynamics of the spring-mass system used in this study are:

$$m_1 \ddot{x}_1 - F_{kx} = F_x \quad (1)$$

$$m_2 \ddot{x}_2 + F_{kx} = 0 \quad (2)$$

$$m_1 \ddot{y}_1 - F_{ky} = F_y \quad (3)$$

$$m_2 \ddot{y}_2 + F_{ky} = 0 \quad (4)$$

where (x_1, y_1); (x_2, y_2) are positions of masses $\mathbf{m_1}$ and $\mathbf{m_2}$ respectively. Forces F_{kx} and F_{ky} denote the x and y components of the forces arising from the action of the spring and the damper; and F_x and F_y are the external forces acting on the system. In a real system, these might be the forces exerted on the mass $\mathbf{m_1}$ through actuators of an *x-y* table.

Without explicitly deriving the expressions for F_{kx} and F_{ky}, we now show that a simple feedback controller can be used for position control of mass $\mathbf{m_2}$. Similar to the approach proposed in [20], we define desired second order dynamics for the end effector ($\mathbf{m_2}$) as

$$\begin{aligned} \ddot{x}_2 + \lambda^2 x_2 + 2\lambda \dot{x}_2 &= -K_p (x_2 - x_d) - K_v \dot{x}_2 \\ \ddot{y}_2 + \lambda^2 y_2 + 2\lambda \dot{y}_2 &= -K_p (y_2 - y_d) - K_v \dot{y}_2 \end{aligned} \quad (5)$$

where (x_d, y_d) is the desired equilibrium point of the end effector and K_p and K_v are control gains.

Now, eliminating $\ddot{x}_2$ and $\ddot{y}_2$ from the set of equations (5) using Equations (1) through (4), we can solve for F_x and F_y. Following this analysis, our controller takes the form of Equation (6):

$$\begin{aligned} F_x &= m_1 \ddot{x}_1 - m_2 (2\lambda \dot{x}_2 + \lambda^2 x_2) \\ &\quad - m_2 K_p (x_2 - x_d) - m_2 K_v \dot{x}_2 \\ F_y &= m_1 \ddot{y}_1 - m_2 (2\lambda \dot{y}_2 + \lambda^2 y_2) \\ &\quad - m_2 K_p (y_2 - y_d) - m_2 K_v \dot{y}_2 \end{aligned} \quad (6)$$

This controller was later used to verify the active assistance (shared control) mode and also movements the subjects were required to perform in order to successfully complete the experiments.

2.2 User Assistance

Haptic assistance to a user in performing a task can be of two types, namely passive or active. Passive assistance is characterized by use of force cues in order to convey performance information to the user as they conduct the task. This may involve use of virtual guides or force fields which exert corrective forces on the haptic interface if the operator chooses an incorrect path. This way the user is usually guided to follow the path of minimum resistance [10-12]. Active assistance on the other hand involves use of shared control or augmentation functions which help the user in actual completion of the task by applying or augmenting forces that play a role in the completion of the task [6-9].

Control of an underactuated system by a human user requires learning of the dynamics of the system by the operator. In order to study the effects of different forms of assistances, both a passive and an active assistance strategy were designed and tested. During passive assistance, a virtual force field exerted forces on the user's hand in case of a perpendicular deviation from the desired motion of mass $\mathbf{m_1}$. The force felt was proportional to the magnitude of deviation.

During early experiments with the system described in the previous subsection, it was found that inexperienced users faced difficulty in suppressing the angular swing of mass $\mathbf{m_2}$. This was primarily due to underactuated nature of the task. Therefore, an active assistance control was implemented, based on the controller discussed earlier in the section, to suppress the swing. The active controller exerted forces on the user's hand which served to restrict deviation of mass $\mathbf{m_2}$ from the desired path (horizontal or vertical motion).

3 Methods

Fitt's Law [17] has been extensively used in literature as a measure of human performance, specifically hand-eye co-ordination. In the Fitt's law task, subjects are asked to alternately tap in the center of two rectangular objects placed side by side. The experiments are repeated with varying between-target distances and varying target sizes. The distance between the targets, the target dimensions, and the movement time are then used to characterize human performance. This task has also become a standard test for measuring performance in human-computer interaction [21, 22] and in teleoperation tasks [23].

A modified Fitt's law task was used to study human performance in control of the underactuated slave in the current study. The subjects were asked to repeatedly cause the end-effector, mass $\mathbf{m_2}$, to alternately hit a fixed pair of targets. More than one set of targets were used for the tests. Intuitively speaking, this should involve a rhythmic movement of the controlled mass, $\mathbf{m_1}$, similar to the control of a yo-yo. This was verified using the control system developed and presented in section 2.1.2.

3.1 Apparatus

An Impulse Engine 2000 joystick from Immersion Inc. was used to provide a high fidelity haptic simulation. The Impulse Engine has two degrees-of-freedom and a workspace of 6" x 6". The device exhibits low back drive friction (< 0.14N) and a high sensor resolution (0.0008"). A visual display of the workspace was also created using OpenGL, with a workspace of 800x800 pixels. The workspace was scaled such that the entire usable range of the IE2000 was utilized. The joystick, in conjunction with the visual feedback, was used to conduct a series of tests to study human control of underactuated systems.

An impedance control mode was used in all the experiments, as illustrated in Figure 2. Two-dimensional motion therefore was sensed at the haptic interface, which in turn displayed forces to the user. Both position and velocity were measured at the interface. It should be noted that for the simulations the joystick itself served as mass $\mathbf{m_1}$. The assistance controllers directly applied forces to the controlled mass, $\mathbf{m_1}$, which were also displayed via the haptic interface. After preliminary experiments with the authors as test subject, the values for $\mathbf{m_2}$, **k** and **b** were chosen to be 5 kg., 5.7 N/m, and 0.17 Ns/m respectively, to ensure the system to be easily controllable. Note that the simulation program uses different units (digital units for both force and length measurements), thus the conversion to Newtons and meters results in non-integer values. Forces at the haptic interface were then scaled to improve user perception. All simulations ran at the sampling frequency of 1 KHz. The system bandwidth for the apparatus is 120 Hz and it is capable of displaying a maximum force 8.9N in the workspace.

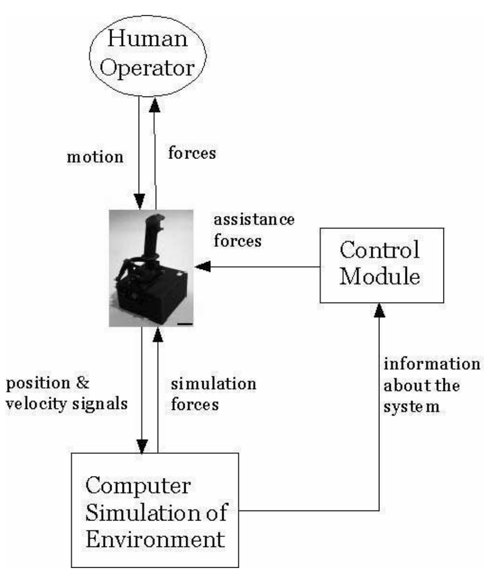

Figure 2. Block diagram of the haptic interface system. IE2000 joystick from Immersion is shown in hardware block.

3.2 Experimental Paradigms

Performance study experiments were conducted for four pairs of targets and varying forms of assistance to the user. Two target sets were aligned along the x-axis and the other two along the y-axis. Each of the targets in a set was equidistant from the origin. Thus, the subjects needed to move the joystick rhythmically, either horizontally or vertically, to alternately hit the targets in a set. There was no attempt to obstruct the subject's view of the other targets.

The assistance modes chosen for the experiment were as follows:

Control Set (C): As evident from the name, this mode served as the control set. No user assistance was provided during these trials.

Passive Assistance Mode (A): In the passive assistance mode, force fields were used to encourage users to follow the horizontal or vertical direction of motion, depending upon the set of targets used. The force field generated forces proportional to either the x or y error in position of mass $\mathbf{m_1}$. These forces were subsequently displayed to the user via the joystick. The stiffness of the force field was equivalent to 22.8 N/m, with a damping of 0.57 Ns/m.

Shared Control Mode (S): This was the active control mode where a controller, similar to the one described in section 2.1.2 was implemented in simulation. The said controller applied calculated forces upon the joystick, which were in addition to the forces due to the system dynamics and were intended to prevent the swing of mass $\mathbf{m_2}$ away from the desired line of motion. For example, with the targets aligned in the horizontal direction, the controller attempts to suppress the vertical motion of mass $\mathbf{m_2}$. The inertia term corresponding to the inertia of mass $\mathbf{m_1}$ (the joystick in this case) was considered negligible, due to the high back drivability of the joystick. The following values were used for the shard control mode: $\lambda = 1$, $k_p = 70$, and $k_v = 1$.

Combined Mode (S+A): Both active and passive modes of assistance were provided to the user in this mode.

The experiments themselves were conducted in two ways. In Experiment 1, the subjects were asked to hit each set of targets a fixed number of times, during which the time between taps was recorded. In Experiment 2, they were given a fixed amount of time (20 seconds) to hit the targets as many times as they could, and the total number of target hits was recorded. The administration of two experiments was intended to show if the change of performance goal had any psychological effect on performance due to the associated accuracy/speed trade-off. The subjects reported that in either mode it was most important to maintain the rhythm when performing the assigned task.

It should be restated here that the both the assistance and shared control modes only affect the motion of the system in the direction perpendicular to the orientation of the active target pair. If the joystick is released by the user, the handle will move such that the motion of either $\mathbf{m_1}$ or $\mathbf{m_2}$ is constrained in this perpendicular direction. However, the control algorithms will not cause $\mathbf{m_2}$ to be drawn towards the active target. Therefore, the subject is required to initiate the side-to-side motion of the joystick necessary to cause successful performance of the task

3.3 Subjects

Eight subjects, three females and five males, all right-handed, were tested. Five of the subjects had limited experience using a haptic interface, whereas the others had considerable prior experience. Neither author served as a test subject owing to extensive exposure to the task under consideration.

3.4 Experimental Procedure

Subjects sat facing the computer screen with the dominant (right) hand holding the IE2000, as shown in Figure 3. They were allowed to perform the tapping tasks a few times in an unassisted mode in order to become acquainted with the task.

Two versions of the Fitts' target tapping experiment were then conducted, and each subject performed each version four times. The first version (Experiment 1) required subjects to alternately hit a designated target pair 13 times in a row. The second version (Experiment 2) required subjects to alternately hit a designated target pair as many times as possible in a 20 second trial.

The active target was displayed in green, while all other targets were red. Target pairs are referred to as Vertical Near (VN), Vertical Far (VF), Horizontal Near (HN), and Horizontal Far (HF) as shown in Figure 4. The targets were at a distance of 120 (near) and 240 (far) pixels from the center of the workspace. Each target is 8 pixels by 8 pixels in size.

The control modes include Control (complete user control), Assistance (passive), Shared (active), and Combined (Assistance and Shared). In all, sixteen combinations of target pair and control mode were presented in each experiment (one occurrence of each target-mode combination). The experiments were presented in alternating order (1-2-1-2… or 2-1-2-1…) to each subject in one sitting. The order of presentation of the target pair-control mode combinations was randomly assigned in the computer code at the start of each experiment. At the conclusion of testing, subjects commented on their strategies for the two experiments. For each experiment, the time elapsed between target hits was recorded. In addition, for Experiment 2, the total number of target hits per trial was recorded.

Figure 3. Test subject seated at IE2000.

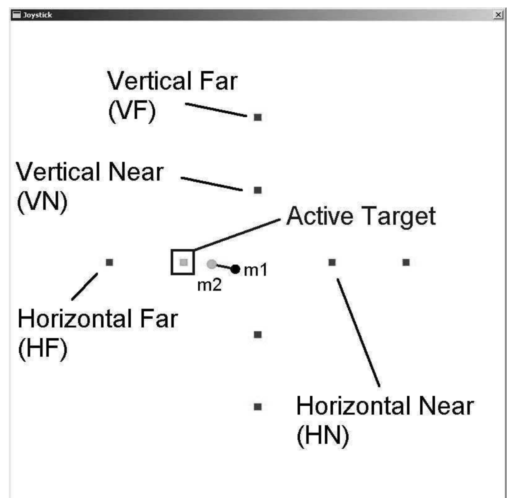

Figure 4. Graphical display of Fitts' tapping experiment with underactuated system.

4 Results

4.1 Experiment 1

In Experiment 1, subjects were asked to alternately tap targets thirteen times in a row in the presence of a control mode. The inter-tap times were recorded for each trial. The average results across subjects for each target pair and control mode are presented in Figure 5.

4.2 Experiment 2

In Experiment 2, subjects were asked to alternately tap targets during 20 second timed sessions in the presence of four different control modes. The number of hits and the inter-tap times were recorded for each trial. The average number of hits across subjects for each target pair and control mode are presented in Figure 6.

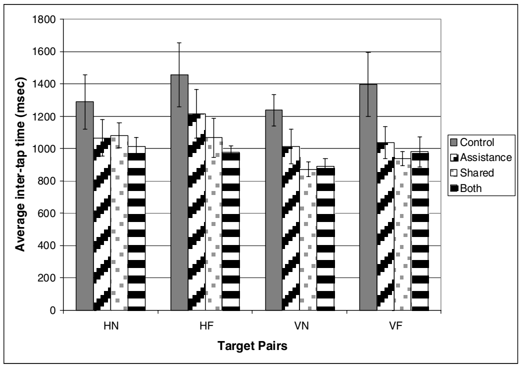

Figure 5. Experiment 1 – average inter-tap time for 13 hits, averaged across subjects, for each target and control mode.

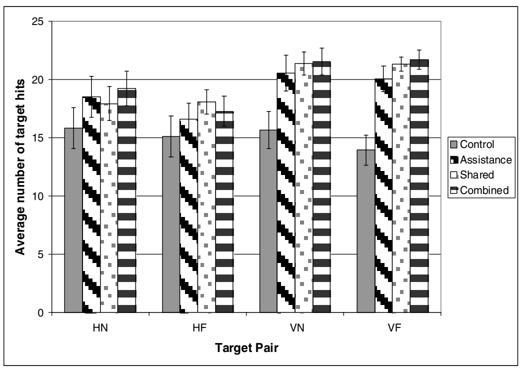

Figure 6. Experiment 2 – average number of taps for 20 sec trial, averaged across subjects, for each target and control mode.

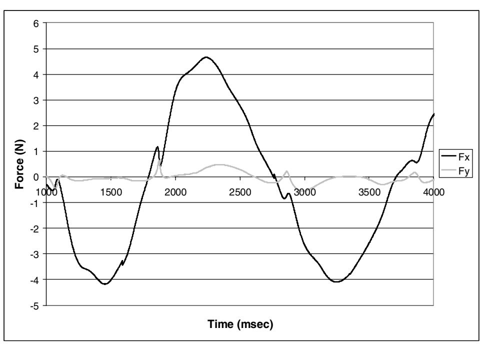

Figure 7. Force output versus time for Control case – User controls all motion of m_1.

4.3 Experimental Force Data

Command forces were recorded versus time for each control mode in order to show the contribution of the assistive forces to the total force command felt by the user. These results are shown in Figures 7 through 10.

In each of these figures, the total force output command is (F_x, F_y). The contribution to the total force command from each control mode is (F_{kx}, F_{ky}) for the spring and damper force, (F_{px}, F_{py}) for the potential force during the assistance mode, and (F_{sx}, F_{sy}) for the force

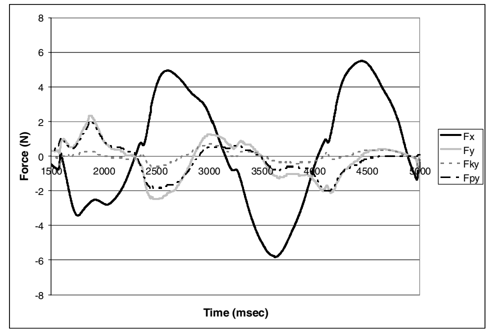

Figure 8. Force output versus time for Assistance case – User controls all motion of m_1 and feels an additional force in the *y* direction if m_1 deviates from a horizontal path between the targets.

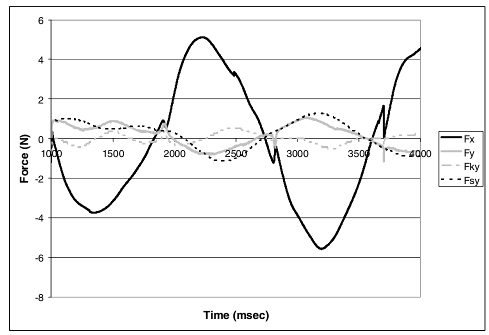

Figure 9. Force output versus time for Shared case – User controls all motion of m_1 and feels an additional force in both *x* and *y* that attempt to drive m_2 to a horizontal path between the targets.

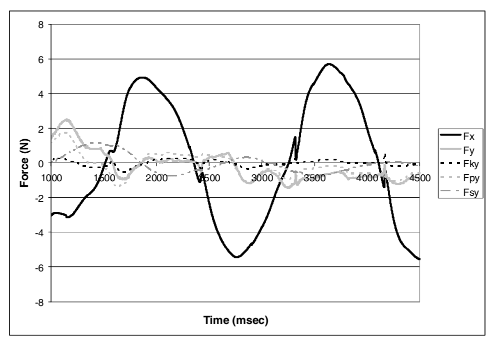

Figure 10. Force output versus time for Combined case – User controls all motion of m_1 and feels additional forces in *x* and *y* due to both m_1 and m_2 deviation from a horizontal path between the targets.

due to the shared control command. All graphs present data for the tapping task with the horizontal near (HN) target pair. Therefore, all assistive forces due to the assistive and shared control modes occur in the *y* direction only.

5 Discussion

In Experiment 1, subjects were asked to tap a constant number of alternating targets in a minimal amount of time. The elapsed time between taps was recorded for each trial and then averaged. These values were then averaged across all eight subjects for each target-control mode pair. As shown in Figure 5, the average inter-tap interval for the assistance, shared and combined control modes was consistently lower than that for the user control mode (no virtual assistance). The combined control mode did not appear to lead to improved performance over the passive or active control modes acting along in terms of this performance measure.

A repeated measures analysis of variance (ANOVA) was performed. For these analyses, the factors were as follows: assistance mode (on/off), shared mode (on/off), orientation (horizontal/vertical), and distance (near/far). According to the analysis, the effect of assistance mode was significant (F(1,7)=20.82, P=0.0026). The effect of shared mode was less significant (F(1,7)=8.06, P=0.0251). The interaction of the two modes was also significant (F(1,7)=19.2. P=0.0032). The only other significant result was the interaction between shared mode and distance (F(1,7)=13.68, P=0.0077). The significance of the effect of the assistance and shared mode was as expected, since it was hypothesized that the assistance modes would improve user performance of the targeting task. The interaction between shared mode and distance could be attributed to the fact that the near target pairs are somewhat easier for subjects to hit, since the range motion of $\mathbf{m_2}$ necessary to hit the target is much less than that for the far targets. This implies that when larger motions are required, the shared assistance mode is more helpful.

In Experiment 2, the total number of hits was used as the performance measure. As seen in Figure 6, performance was notably better for the assistance, shared, and combined control modes compared to the user control mode. According to the repeated measures ANOVA analysis, the effect of assistance mode was significant (F(1,7)=41.26, P=0.0004), as was the effect of shared mode (F(1,7)=52.11, P=0.0002). The interaction of the two modes was also significant (F(1,7)=61.41. P=0.0001). The only other significant results were the interactions between shared mode and distance (F(1,7)=13.79, P=0.0075), between shared mode and orientation (F(1,7)=17.11, P=0.0044), between assistance mode and orientation (F(1,7)=15.84, P=0.0053), and between assistance mode, shared mode, and orientation (F(1,7)=29.81, P=0.0009). Again, we see highly significant effects of both the assistance and shared modes, which supports the hypothesis that these modes will improve user performance of the task. Higher levels of significance for this experiment compared to Experiment 1 could be attributed to the fact that, on average, subjects were able to hit more than 13 targets in the allotted time of twenty seconds. Therefore there is a larger range of scores that are compared. Interactions between the control modes and the orientation of the target pairs were common for this experiment. This is likely due to the fact that for the horizontal pairs, motion is primarily seen in the wrist of the subjects, while for the vertical target pairs, motions arise from the wrist and forearm in order for the targets to be reached. Because greater motions are required to hit the vertical targets, the assistance and shared modes contribute to improved scores. This phenomenon is most evident in Figure 6. Here we see that for the unassisted modes, scores are generally better for the horizontal pairs than for the vertical target pairs. However, when either assistance, shared, or combined modes are activated, performance is better for the vertical target pairs.

The authors noted slight improvements in performance on a subject-by-subject basis as they progressed through the experiments, yet there was insufficient data to verify that this trend was significant. This indicates, however, that the control modes may contribute to improved performance of the task over time. It is not known if these improvements would be due to practice of the task or due to training effects conveyed in the assistance, shared, and combined control modes. These trends will be investigated in future work, since it is hypothesized that the active assist modes will improve training effectiveness for dynamic tasks.

Another focus for future study is the effectiveness of the active assist training in terms of transfer to real tasks. An "on" or "off" approach to the use of virtual fixtures in training may improve performance during training, but performance in a "real-world" task may be in fact worse since the subject has learned to rely on the presence of the virtual fixtures in the virtual training environment. This phenomenon has been seen when augmented feedback such as computer enhancement of the environment has been added to a graphics-only virtual environment. Todorov and others noted that although some forms of augmented feedback in a graphical virtual environment were shown to enhance learning of simple movements, the performance gains achieved during training seldom transferred to the real task [24]. Future work will study the merit of adaptive assistive forces displayed in conjunction with simulated system dynamics for training or rehabilitating subjects.

6 Conclusions

We have demonstrated that both passive and active assistance during completion of a dynamic targeting task serve to improve human performance of the task in terms of between target tap times and number of hits per trial. Baseline results are tabulated such that performance and transfer of training to a real environment can be further investigated in future research efforts.

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