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Chapter *in* IFMBE proceedings · April 2010

DOI: 10.1007/978-3-642-03889-1_55

Proceedings of the 11th World Congress on Medical Physics and Biomedical Engineering,
September 7-12, 2009 in Munich, Germany

On the Efficacy of Haptic Guidance Schemes for Human Motor Learning

Volkan Patoglu[1], Yvonne Li[2], and Marcia K. O'Malley[2]
[1] Faculty of Engineering and Natural Sciences, Sabancı University, İstanbul, Turkey
[2] Department of Mechanical Engineering and Material Science, Rice University, Houston, USA

***Abstract*— This article investigates the efficacy of different haptic guidance schemes on human motor learning. In particular, the performances of four training protocols, virtual practice, virtual fixtures, fixed-gain error-reducing shared control, and progressive error-reducing shared control, are compared. The experimental results indicate that, if not designed carefully, haptic guidance protocols may be detrimental on motor learning, since such schemes actively interfere with the coupled system dynamics and cause participants to experience task dynamics that are altered from those of the real task. Results also show that the amount of assistance is an important factor, and fixed-gain assistance schemes may cause subjects to gain dependence on the existence of the guidance. Adjusting the amount of haptic guidance based on performance, utilizing progressive gains, is shown to increase the training effectiveness when compared to fixed gain controllers. Key parameters that influence the principles of motor learning in healthy human subjects may guide the design of more effective rehabilitation training protocols.**

I. INTRODUCTION

Assistance of repetitive and physically involved rehabilitation exercises using robotic devices not only helps eliminate the physical burden of the movement therapy for the therapists, but also enables safe and versatile training with increased intensity. Robot assisted therapy can be used to treat patients with all levels of injury, allows for quantitative measurements of patient progress, and can be tailored to induce patient specific treatment protocols. With the addition of virtual environments and haptic feedback, these devices can be used to realize new treatment protocols; hence, promise to improve the efficacy of treatment.

In the literature, beneficial effects of robot assisted rehabilitation over conventional therapy have been demonstrated. However, the magnitude of benefits achieved over conventional therapy in terms of functional outcome has only been modest. The limited success of early implementations of rehabilitation systems is attributed to the human-machine interface established by the controller design of these devices that does not allow for active involvement of patients. Specifically, many of these devices employ robots as non-accommodating trajectory generators, while the patients are expected to behave as passive subjects. Recent studies suggest that intervention methods that emphasize the active involvement of patients in the physical therapy routine and provide assistance to the patient *as needed* in order to render the task completion feasible, possess the potential to have positive influence on the efficacy of the rehabilitation therapies.

Unfortunately, only a limited amount of clinical evidence is available on how to optimally engage patients. The relationship between many of the proposed intervention protocols and their clinical outcomes is yet to be studied. The design of effective treatment schemes is not a trivial task and the investigation of the optimal intervention scheme though trial and error techniques is prohibitive due to time consuming nature and high cost of clinical trials. Hence, a more effective framework is necessary to study rehabilitation protocols.

Since it is the plasticity of CNS that enables injured people to recover and healthy people to learn new motor skills, the principles of motor learning in healthy subjects may guide the design of effective treatment protocols. Even though one cannot assume that the damaged CNS learns in the same manner as the intact one, the key parameters that influence acquisition of skill may be relevant for both cases.

This article investigates the efficacy of different haptic guidance schemes on human motor learning. In particular, the performance of four training protocols, virtual practice, virtual fixtures, fixed-gain error-reducing shared control, and progressive error-reducing shared control, are compared with a long-term human subject experiment. The possible detrimental influence of haptic guidance schemes on learning is demonstrated. The importance of the amount of assistance is discussed and the efficacy of progressive gains over fixed gains is shown. These results are relevant to the rehabilitation literature, since the principles of motor learning in healthy subjects may guide the design of more effective treatment protocols.

To date, several performance-based assistance schemes have been implemented in the field of rehabilitation robotics. In [1], a performance-based progressive robot-assisted therapy for stroke patients was implemented. The patients were provided with haptic guidance during a reaching task by means of a virtual spring pulling them towards the target. The spring coefficient, hence the amount of guidance, was adjusted based on the performance of the patients. Unfortunately, no conclusive training results are reported for this study. In another study for gait training, human motor adaptation to dynamic environments was modeled as an error corrective learning process and the control gains of the guidance robot were adjusted at each trial based on the error [2]. The results from the interaction simulations of this study suggest that providing guidance as needed is more effective than always assisting with a fixed amount. Similarly, in [3] assist-as-needed protocols have been proposed and tested for gait training. The results of our study provide further experimental evidence on the positive efficacy of progressive gains over fixed gains while assisting task completion and supports use of assist-as-needed protocols in the rehabilitation literature.

II. Methods

A. Task

The task for the training experiment is a target-hitting manual control task. Participants view a virtual double-mass spring system on a computer monitor and are asked to control the motion of mass m_1 via a two DoF haptic device, a joystick. Through the two-mass system's dynamics, the participants are able to indirectly control mass m_2 to alternately hit a fixed pair of targets. The targets are equidistant from the origin; therefore, the participants need to move the joystick, directly coupled to m_1, rhythmically, along the sloped path (referred to as the target axis), to cause m_2 to alternately hit the target pair. The task objective, as presented to each participant, is to hit as many targets as possible in each 20 second trial.

B. Participants

Thirty-two participants (8 females, 24 males, ages 18–33, 1 left-handed), primarily undergraduate students in engineering, participated in the experiment.

C. Performance Measures

Two performance measures were analyzed to assess participant performance for the target-hitting task, namely normalized hit count and average error. Normalized hit count is the total number of target hits within one trial normalized by the natural frequency of the corresponding dynamic system. Average error is the average of the instantaneous trajectory errors of mass m_2. Together, these performance measures capture the features of the task, where normalized hit count gives an assessment of speed of execution, while average error monitors the ability of the participant to maintain a trajectory along the target axis. Average error is treated as a secondary performance metric, since participants are not specifically instructed to reduce the deviation of m_2 from the target axis. Nevertheless, these two measures provide a means for the proposed haptic guidance schemes to be objectively compared.

D. Haptic Guidance

The four different haptic guidance schemes presented and subsequently compared in this experiment are virtual practice, akin to no assistance (N), virtual fixtures (V), fixed-gain (S) and progressive error-reducing (P) shared controllers. In the virtual practice (N) mode, participants felt the forces generated solely due to the internal dynamics of the 2 DoF system. In contrast, for the virtual fixtures (V) and shared control cases (P and S), participants felt the forces due to both the internal dynamics of the system and the guidance forces intended to assist.

In the virtual fixtures (V) guidance mode, virtual walls were used to encourage users, in a passive manner, to move mass m_1 along the target axis, thereby causing m_2 to settle along the same path. The virtual walls generated forces proportional to the deviation and velocity of mass m_1 normal to the x-axis. In the error reduction implementation of shared control (P and S), the dynamics of the (state dependent) shared controller are designed such that the coupled (closed loop) dynamics of the system are simpler to manipulate than the system dynamics without the controller in place. In particular, this training scheme differs from the virtual fixtures in that perceptual constraints are not implemented on user input but on user output, and are reflected to the user through the inverse dynamics of the system to be controlled. The detailed implementation of error reducing shared controller is described in the authors' previous works [4].

The performance-based progressive algorithm was employed to determine the gains of the controller during assistance subsessions for progressive shared control (P). The input performance measurement for the algorithm was the normalized hit count since it is the primary goal of the task. The progressive shared controller (P) started with the same control gains as fixed-gain shared controller (S). The progressive shared control gain update law was controlled by a rolling average of three consecutive trials. Once the average of the current trial and two previous trials (average 2) is larger than the average of previous three trials (average 1), the control gain decreases. On the other hand, if average 2 is smaller than average 1 for three consecutive trials, control gain increases. Furthermore, if the absolute value of average 1 is above a certain threshold, 30 normalized hit counts, the control gain decreases. The control gain was adjusted based on the ratio of difference between average 1 and average 2 over average 1. This update law, similar to the one-up three-down scheme described by Levitt [5], aims to decrease the haptic guidance, thereby decreasing the dependence on the guidance while the participant's performance still increases. In this way the progressive shared control scheme approaches virtual practice toward the end of training. Figure 1 depicts the decaying progressive shared control gain of a typical participant.

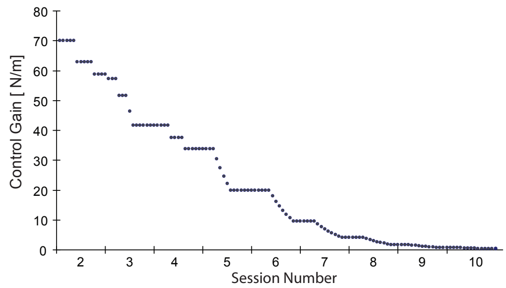

Fig. 1. Progressive shared control gain of a participant during assistance sub-sessions #2-10 illustrates the typical decaying trend. Decreasing gain is indicative of improving performance in terms of normalized hit count.

E. Experiment Design

The experiment was composed of 11 sessions, including an evaluation session, nine training sessions, and a retention session. Each training session contained three subsessions: pre-assistance baseline, assistance, and post-assistance baseline. Each subsession consisted of 14 trials, with each trial lasting 20 seconds. Details of the experiment design are schematically represented in Figure 2.

F. Procedure

Before the experiment, each participant was given a maximum of five minutes to become familiar with the haptic joystick and the virtual task. In order to control for individual differences in performance, each participant was asked to

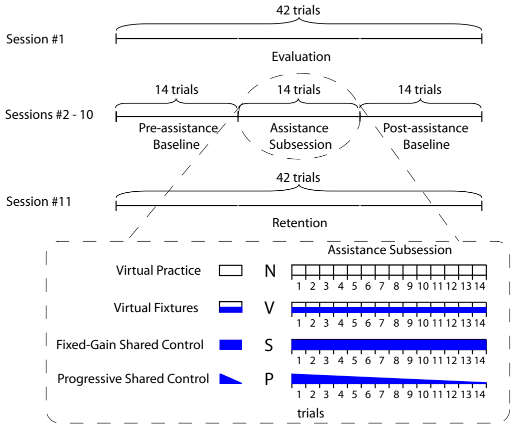

Fig. 2. Experiment consists of one evaluation, nine training and one retention session. Each training session contains three subsessions: pre-assistance baseline, assistance, and post-assistance baseline.

perform the task in an evaluation session, administered without haptic guidance. Then, participants were assigned to one of four training protocols based on their initial performance of the target-hitting task.

All groups completed one evaluation session, nine training sessions, and one retention session. The virtual practice (N) group served as the control set with no haptic guidance provided during assistance subsessions of the protocol. In order to assess the improvement of participants across the nine training sessions, baseline subsessions of 14 trials administered without guidance were completed before and after each assistance subsession. One assistance subsession and its corresponding pre- and post-assistance baseline subsessions took place in one 30 minute session. The nine training sessions were separated by two to three days, such that the participants completed all the sessions in no less than three but no more than four weeks. One month after the final training session, all participants were recalled to complete one retention session. In the evaluation and retention sessions, no haptic guidance was provided to any participants.

G. Data Analysis

Repeated measure ANOVAs were utilized to determine significance of results. The guidance mode was between-subjects, with levels virtual practice (N), virtual fixtures (V), fixed-gain (S) and progressive (P) shared control. The session factor was within-subjects, with levels of evaluation, training (9 in all), and retention, for a total of 11 levels. Difference of least square means is used as the multi comparison strategy.

III. Results

Figure 3 shows the results for all four groups in the post-assistance baseline subsession in order to compare the efficacy of different haptic guidance schemes. The performance of all groups improved significantly in terms of both performance measures (normalized hit count and average error) and saturated near the end of training. A repeated measures ANOVA with between-subject factors (group as between-subject factor, session as within-subject factor) was carried out to determine significance of results for these four groups. The results revealed a significant main effect of group and session for the post-assistance subsessions in terms of both normalized hit count and average error. Summaries of ANOVA and all pertinent multi comparisons at post-assistance are listed in Tables I and II, respectively.

Figure 3, Tables I and II reveal that S group exhibits

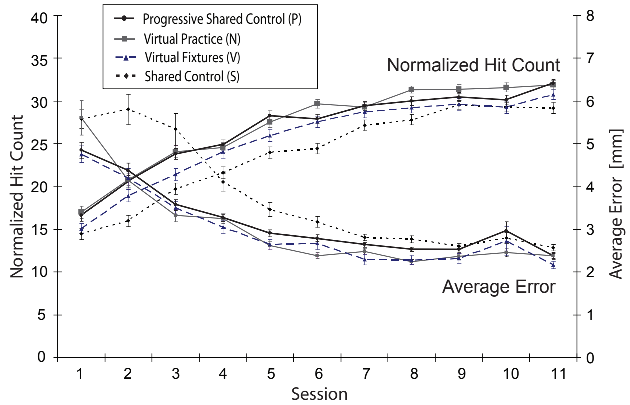

Fig. 3. Post-assistance baseline normalized hit count and average error plots for different haptic guidance groups over eleven sessions of the training protocol.

TABLE I
Summary of Significance of Factors

Measure	Effect	post-assistance
Normalized Hit Count	Group	$F(3,444) = 13.29,\ p < 0.0001^*$
	Session	$F(8,437) = 182.58,\ p < 0.0001^*$
	Interaction	$F(24,1268) = 2.28,\ p = 0.0004^*$
Average Error	Group	$F(3,444) = 19.67,\ p < 0.0001^*$
	Session	$F(8,437) = 67.16,\ p < 0.0001^*$
	Interaction	$F(24,1268) = 3.33,\ p < 0.0001^*$

TABLE II
Summary of Significance for Multi Comparison

Group Comparison	Average Error	Normalized Hit Count
S vs. N	$p < 0.001^*$	$p < 0.001^*$
S vs. V	$p < 0.001^*$	$p < 0.001^*$
S vs. P	$p < 0.001^*$	$p < 0.001^*$
N vs. V	$p < 0.001^*$	$p > 0.05$
N vs. P	$p > 0.05$	$p > 0.05$
V vs. P	$p = 0.003^*$	$p = 0.042^*$

the worst performance among all the groups in terms of both normalized hit count and average error. V group is significantly worse than N and P groups in terms of average error, while is not significantly different from N group in terms of average error. P group exhibits performance at least as good as N group in terms of both normalized hit count and average error.

IV. Discussion

Among all the haptic assistance training paradigms tested in this study, P group is the only training protocol that has comparable overall performance to N group (virtual practice). This result indicates that fixed-gain guidance schemes (V and S) in fact have negative training efficacy and these paradigms are less effective for training of motor skill than practicing without assistance forces.

To further explore the negative efficacy of S and V groups, learning trends within a session and across sessions are analyzed in Figure 4 for the hit count performance. Figure 4 consists of two plots: a line plot displaying absolute task performance improvement within a session, with each line segment corresponding to one training session, and a bar plot representing the percent change of performance within a session. For both plots, the data represents a comparison of the average performance of the last three trials of the pre-assistance baseline subsession to the average performance of the first three trials of post-assistance baseline subsessions. These values characterize within session performance of a group just before and just after the assistance subsession, quantifying the amount of learning that occurred within the assistance subsession. As depicted in Figure 4, all groups

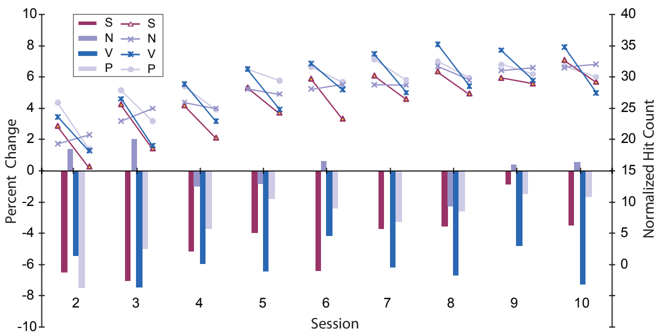

Fig. 4. Absolute task performance (line) and performance change percentage (bar) plots in terms of normalized hit count for all groups over nine training sessions (sessions #2-10).

start from approximately the same performance level in terms of normalized hit count at session #2; however, the slope of the within session learning curve becomes negative for the S and V groups after the first assistance subsession and remains negative during early subsessions. The existence of negative learning in early sessions of training for S and V groups indicates that guidance provided during the assistance subsessions significantly interferes with learning. The interference exists since the haptic guidance modifies and augments the system dynamics in order to assist task completion and the assisted task becomes a secondary task to be learned.

The existence of interference is a major concern that results in negative learning efficacy of fixed-gain guidance paradigms that are designed to improve task performance. Even though all three groups exhibited approximately the same amount of interference at the beginning of training, for P group this interference decreased progressively as the training proceeded (see Figure 4). In the case of V group, the performance difference fluctuated and remained at the similar level throughout the training, while for S group, the difference experiences an overall decreased but still maintained at a relatively higher level when compared to P group. The different trends among these three groups indicate that each training paradigm results in different interference characteristics.

The normalized total guidance force provided during the assistance subsession is introduced as a way to investigate how much the human participants depend on the existence of the haptic guidance. The normalized measure for each assistance subsession is calculated as the percentage change of the total guidance force provided within the session, compared to the total guidance force provided during the first session. This measure serves as an indicator of the amount of guidance provided by each of the haptic guidance methods and is recorded in Figure 5 for all three haptic guidance groups. Figure 5 shows that P group decreasingly depended

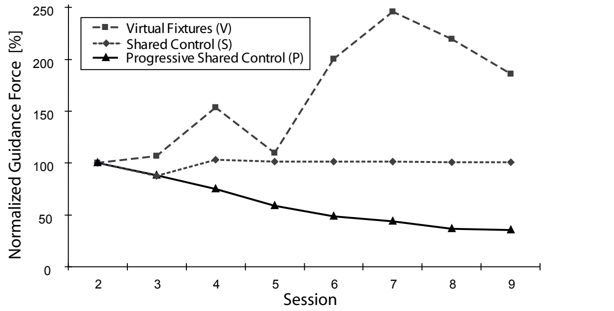

Fig. 5. Total guidance force during the assistance subsessions for all three haptic guidance schemes demonstrates that the progressive shared control (P) group depended decreasingly on the guidance while the other two groups throughout the training protocol continued to depend on the guidance provided. Results are normalized based on the amount of guidance force incurred in the first session of training.

on the guidance throughout the protocol. With less and less assistance provided from the haptic guidance paradigm, the performance of P group kept increasing. Therefore, the increasing performance of the P group is *not solely* due to the existence of assistance, but due to the skills the participants acquire during training. Contrary to S and P groups, V group exhibited an increasing trend in terms of total assistance force experienced. This fluctuating yet increasing average trend indicates the heavy reliance of V group on the assistance.

These results indicate that the performance-based progressive algorithm has a positive effect in reducing interference and dependency over the other forms of fixed-gain haptic guidance that assist task completion. However, P group does not necessarily exhibit better performance than virtual practice. One possible reason for this result maybe due to the incomplete design of the shared controller. According to [6], during training, a task should be simplified only if the important perceptual invariants of the task are preserved. In the current implementation, the shared controller assists position control perpendicular to target axis, but neglects the temporal aspect of the control task: exciting the system near its resonant frequency along the target axis. A redesign of the progressive shared controller to capture all critical aspects of the manual control task may lead to significantly better training performance than virtual practice.

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