# Haptic Motion Training: Exploring Learning Environments for a Portable Gait Retraining System

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## ABSTRACT

We explore the potential for a portable gait retraining system, which provides real-time haptic feedback to a user who is occupied with other tasks. We present a study that compares the effects of attention and haptic feedback on learning and retention of a new gait to understand whether humans can learn a new gait when distracted and if real-time haptic feedback can enhance the process. We find that subjects are able to approximately learn the new gait under all conditions, but subjects had better learning and retention with full attention on the training and with haptic feedback on every step. Our results support the idea that a portable real-time haptic feedback system has promise for facilitating motion training.

**ACM Classification:** H5.2 [Information interfaces and presentation]: User Interfaces. - Haptic I/O

**General terms:** Design, Human Factors, Experimentation

**Keywords:** Motion training, haptic feedback

## INTRODUCTION

Motion training has many applications from sports to physical therapy to musculoskeletal disease treatment. With advances in motion tracking systems and computing, the development of a portable motion training system is increasingly viable. Such a device would allow users to train in real-world environments, but this system has limitations. A user may not have constant access to feedback from a human expert and may be doing other tasks (e.g. having a conversation) while training. Automated feedback, then, needs to provide sufficient information to the user so that he can correct his movements. And since other tasks may require the use of auditory and visual channels, the feedback should use an alternate modality.

As a viable option, we propose a real-time haptic feedback system supplemented with a graphical display that a user can consult periodically. We chose gait retraining, which has been shown as a promising treatment for knee osteoarthritis [7], as an example application to test the system.

### Related Work

The design of our system is rooted in previous research in motor learning and in the use of feedback, particularly haptic feedback, for motion training tasks.

*How We Learn* In order to walk, humans develop a motor program that organizes the actions for the complex task. Thus, to modify a user's gait, it is necessary to transform his internal model through external feedback. The design space for a feedback protocol is large, though content, amount, precision, and frequency are amongst the most important features to address. The real-time haptic feedback will provide frequent knowledge of performance, or precise kinematic information required to achieve the desired motion. The supplementary visual display will provide knowledge of performance that summarizes progress over a longer duration. Both types of feedback have proved useful for learning and retention [6].

*Promise of Haptic Feedback* Haptics is a promising modality for providing kinematic feedback. Because haptic devices can be placed at specific physiological locations, there are minimal spatial and sensorimotor transformations that must occur to translate the given proprioceptive feedback to a motor response [4].

Haptics also shows promise when used in limited attention situations. Huang et al. demonstrated that users are able to learn simple piano passages through haptics while answering SAT questions [2]. Additionally, Gray et al. demonstrated that haptic cues can redirect attention while users are engaged in a visual task [1]. Haptic feedback has been used to enhance motor performance in many tasks. In particular, others have shown a spatially-distributed tactile interface aids motor learning. The TIKL, for example, is a wearable tactile vest that allows users to quickly learn new quasi-static motions through visual and haptic guidance [5]. And, we have previously demonstrated that subjects can modify their gaits using only haptic feedback within a thirty-minute training session [7]. While the spatially-distributed tactile interface is not unique, we wish to better understand its efficacy for a portable gait retraining system.

### Research Questions

Motion learning and retention are two important metrics for evaluating a gait retraining system. To assess a system in which a subject receives real-time haptic feedback in partial attention situations, we asked the question: Does a gait retraining system provide (1) comparable learning and retention between full attention and partial attention environments and (2) improved learning and retention with real-time haptic feedback over a system with no haptic feedback?

We hypothesized that:

Figure 1: Gait modifications and feedback schemes for foot (left) and trunk (right). Vibration motors in red vibrate when motion is not correct providing subject with a pushing sensation towards the desired movement.

*H1. Subjects will improve learning and retention when trained with full attention in comparison with partial attention on the task.* Due to the limited attentional capabilities of humans, we anticipated that learning and retention would be diminished when subjects were required to multitask between a distraction and haptic gait retraining.

*H2. Subjects will have improved learning and retention when haptic feedback is present versus when it's absent.* Real-time haptic feedback could allow subjects to quickly compare the feedback with their motions. This dynamic interplay between feedback and motion is absent without haptic feedback. Thus, we believe its presence will significantly increase learning and retention .

## METHOD

In accordance with Stanford University's Institutional Review Board, we conducted several pilot studies to optimize the haptic feedback design and a main study to answer our research question.

### Experimental System

To train subjects, we used a setup composed of a sensing system to capture the subject's motions, a controller system to determine the type of feedback to provide on each step, and feedback devices (vibration motors) spatially-distributed on the subject's body. [7]

Subjects wore 13 reflective markers to define foot, shank, thigh, pelvis, and trunk segments. Marker data was read in real-time at 60 Hz using a Vicon 3D motion tracking system. Ground reaction forces were measured through a Bertec treadmill at 1200 Hz. A Matlab script calculated joint angles and ground-reaction forces by querying marker data from the Vicon software in real-time. Based on these values, the script computed the desired feedback. The vibration motors were controlled with Matlab's xPC Target. C2 Tactor motors from EAI were selected as vibration motors as amplitude and vibration frequency can be controlled independently.

### Gait Parameters and Feedback Schemes

Gait modifications consisted of changing two gait parameters: toe-in and trunk sway. As shown in Figure 1, toe-in requires the subject to walk with her toes pointed inward while her foot is on the ground; trunk sway requires the subject to rotate his trunk to either side from its base as he walks. Subjects were required to increase their toe-in and trunk sway angles by 5°-10° and 3°-7°, respectively, from their baseline values. These modifications represent a small, but significant change as the magnitude of these changes are between 2-3 standard deviations from a subject's normal gait.

To optimize how the haptic feedback was presented, we conducted pilot studies with 6 subjects. Subjects were presented with several feedback schemes for modifying trunk sway and toe-in angles. These schemes varied in the number, location, and signal of the vibration motors. In all schemes, motors vibrated at 250 Hz for at maximum 0.5 s. Subjects preferred schemes that used two vibration motors for each parameter with placement close to the maximum moment arm. They favored signals that "pushed" them in the correct direction. For example, if the subject was toeing-in too much the motor on the inside of his foot would vibrate, directing him to move his toe outwards. Figure 1 shows the location of the vibration motors and this "pushing" feedback scheme.

### Gait Retraining Experiment

We conducted a study with 19 subject (9 females, 10 males). Subjects were Stanford students or faculty with varying degrees of athletic training.

Subjects were first taught the two gait parameter modifications individually. They were provided verbal and pictorial descriptions of the motions, and then walked for 50 steps with haptic feedback and brief verbal coaching, if necessary. This brief session was meant to ensure that the subjects understood the feedback and the motions. From our pilot studies we learned that if subjects did not understand the desired motions before the main trials began they had little chance of discovering them, and would simply ignore the feedback.

After the initial training, subjects were directed to combine both gait parameter changes, and they practiced the desired gait for 10 trials of 50 steps each. Between trials, they re-

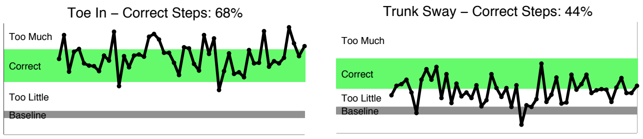

Figure 3: Summary graph, presented after each trial. Steps inside the green box are considered correct.

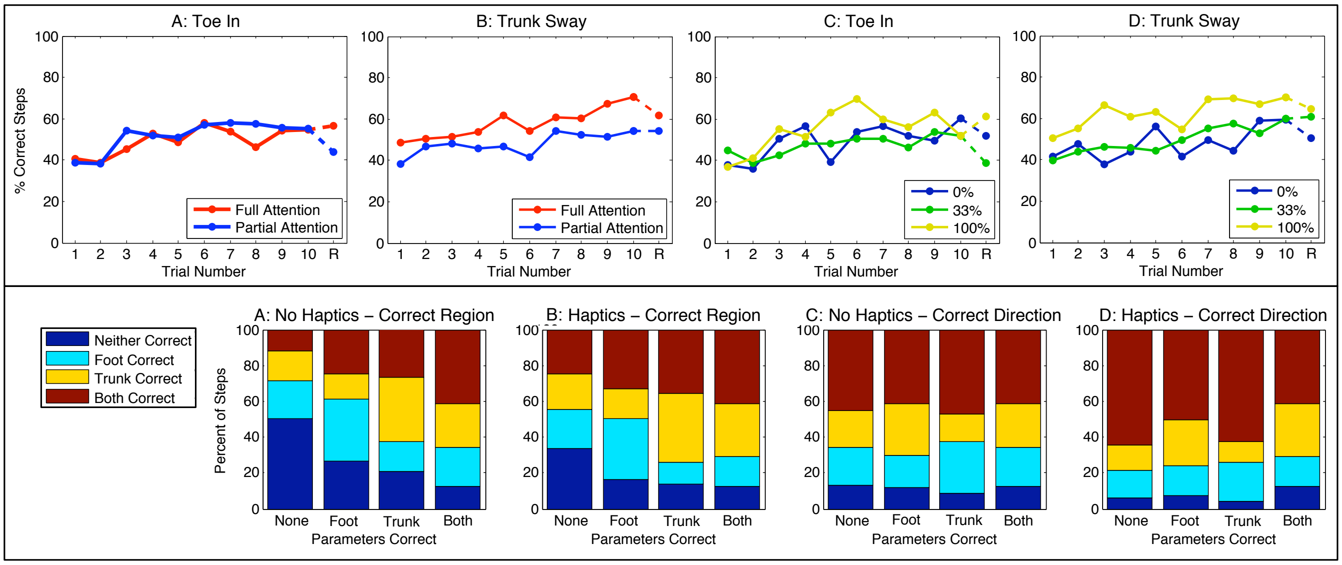

Figure 2: Top: Percentage of correct steps for different attention (A,B) and feedback (C,D) conditions. Bottom: Distribution of decision making for haptics (A,C) and no-haptics (B.D)

ceived a summary graph, similar to the one presented in Figure 3, that showed their performance over the previous trial. Following the last trial, subjects rested for 10 minutes and filled out a questionnaire describing how comfortable they felt with the feedback and gait modifications. Finally, they were instructed to repeat the gait they had learned without any feedback as a measure of gait retention.

Subjects were randomly assigned to one of 6 groups representing feedback and attention conditions for learning the gait in the 10 main trials. Each group had between 3 and 4 participants. Subjects were assigned to one of three feedback groups (0%, 33%, 100%), which represented the percentage of steps that haptic feedback would be provided. The 0% condition was absent of haptic feedback, whereas the 33% and 100% conditions were chosen to show the potential usefulness of haptic feedback. Subjects in the 100% condition received feedback on every step, and subjects in the 33% condition received feedback on every third step. We included the 33% condition because subjects in the pilot studies felt distracted by getting feedback on every step, and it has been suggested that lowering the frequency of knowledge of performance may increase long-term retention [9]. Subjects were also assigned to a partial or full attention condition. These two conditions allowed us to address the role of attention in learning a new gait. Subjects in the partial attention condition played condition participants played FreeRice [8], a multiple-choice vocabulary game which they played with a wireless remote control. Subjects in the full attention condition could devote all of their attention to the motion training.

## RESULTS

### Overall Learning and Retention

We evaluated whether subjects were adequately able to learn and retain the desired gait. Student's t-tests comparing the subject's baseline toe-in and trunk sway angles to the values in the last learning trial (trial 10) and the retention trial (trial 11) showed that all subjects significantly ($p < 0.001$) changed both gait parameters from baseline in these trials. Table 1 shows that the majority of subjects achieved an average trunk sway and toe-in angle within the desired range both in trial 10 and 11, and the overall maximum deviation from the desired range never exceeded a few degrees.

Table 1: Overall learning and retention with respect to desired gait parameter ranges

| | % Subjects in Desired Range | Maximum Deviation |
|---|---|---|
| Trunk Sway Learning | 74% | 1.1° |
| Trunk Sway Retention | 63% | 1.1° |
| Toe-In Learning | 89% | 2.5° |
| Toe-In Retention | 58% | 1.9° |

### Comparative Learning and Retention

We chose among several metrics (e.g. average error from desired region, percent improvement from first trial) to evaluate learning and retention, but none showed any statistically significant results when we compared the metrics between conditions in a given trial. For the remainder of the paper, we will report learning and retention as accuracy, the percentage of steps in which a gait parameter falls within the desired range for a given trial and subject. A comparison between the average accuracy over the trials between partial and full attention conditions is shown in Figure 2A-B (Top) and between the haptic feedback conditions in Figure 2 C-D (Top).

### Evaluating Decision Making

We define decision making as the choice to change gait parameters in the right or wrong direction towards the desired region (or to the desired or undesired region) based upon the correctness of gait parameters in the previous step. For example, when both trunk sway and toe-in are incorrect, what percentage of the time will a subject move both parameters in the correct direction (or move both parameters to the desired region)? We evaluated decision making in the various feedback and attention conditions to understand the differences based on these factors. Figure 2 (Bottom) represents a comparison between the 100% and 0% haptic feedback conditions. To evaluate whether differences in decision making varied significantly between attentional and feedback conditions, Monte Carlo simulations (using data from over 10,000 steps) were performed and yielded highly significant results in many cases.

## DISCUSSION

### Role of Attention on Learning and Retention

Subjects in the full attention condition did not significantly outperform subjects in the partial attention condition in either learning or retention. However, Figure 2A-B (Top) reveals some interesting trends between the two attentional conditions. On average, subjects in the full attention condition were more accurate in the retention trials for both gait parameters. Toe-in accuracy was roughly similar between the partial and full attention conditions, whereas trunk sway accuracy was higher for full attention. The difference between these two parameters may be because of the differences in the motions themselves or the corresponding feedback. Trunk sway has more of an attentional demand as it requires subjects to constantly monitor their trunk angle throughout a step; toe-in only requires the subject to set a foot angle right before her foot hits the ground. Further, subjects found the toe-in feedback more intuitive than the trunk sway feedback (4.3/5 v. 3.2/5 with $p < 0.001$), which suggests that subjects needed less attention to transform feedback to desired motion for toe-in.

### Role of Haptics on Learning and Retention

There was no statistically significant difference between the three haptic feedback conditions (0%, 33%, and 100%). Again, there are some notable trends between the three conditions as evidenced by Figure 2 C-D (Top). The accuracy for learning in the 100% condition is greatest in general for both gait parameters, and most notably for trunk sway. A comparison between the decisions a subject makes with haptic feedback and without haptic feedback indicates why this might be so (Figure 2 (Bottom) ). Subjects with haptic feedback move in the correct direction (and correct region) more often than subjects without haptic feedback. One exception is when subjects do not receive any feedback (both parameters are correct); here, subjects with and without haptic feedback roughly make the same decisions. This result suggests that haptic feedback demands attention and subjects are able to compensate more accurately as a result of the feedback in comparison to subjects without any haptic feedback.

One caveat is that providing feedback on every step will make subjects dependent on it, and thus unable to reproduce the motion when feedback is absent. However, accuracy in the retention trial is highest in the 100% feedback condition for both gait parameters. According to Winstein, who argues that decreasing the frequency of feedback will increase retention [9], the retention the 33% feedback condition was expected to be higher than in the 100% condition. One potential explanation is that the feedback in the 33% condition is misleading: the subject receives no haptic feedback when she completes a step correctly or the step is not one of the 33% of steps she is receiving feedback on. The subject may interpret incorrect steps as correct leading to learning the gait incorrectly.

### Future Work and Final Remarks

Our future work is motivated by the main limitations of our study. Subjects were able to learn the gait modifications relatively accurately in all conditions (Table 1), but there were no statistically significant differences. High variability between subjects dominated the variation between the conditions. A within-subject experiment may provide improved insights about the influence of haptic feedback and attention on gait retraining. For such an experiment, a single subject may learn various gaits with different haptic or attentional conditions. Additionally, our hypothesis was evaluated at the very beginning of gait retraining. Actual users of the system would be required to train for much longer periods of time (several hours at minimum). To better reflect the real-world application, it would be useful to reevaluate our hypotheses over longer training sessions.

This work shows that haptic feedback has a positive influence on learning and retention, and that new gaits can be learned and retained when a person can only devote partial attention to the training task. These results suggest that portable haptic gait retraining system that is used with partial attention has a potential to improve motion learning and retention.

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