Uni- and Bi-directional Haptic Human-Human Interaction During Upper- and Lower-Limb Tracking Tasks

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Abstract. Haptic human-robot-human interaction allows users to feel and respond to one another's forces while interfacing with separate robotic devices. For both upper- and lower-limb tasks, previous work has shown that virtual interactions with a partner can improve motor performance and enhance individual learning. However, whether the mechanism of these improvements generalizes across different human systems is an open question. In this work, we investigate the effects of dyadic interaction during a trajectory tracking task involving single-joint movements at the wrist and ankle. We compare tracking performance and muscle activation during haptic conditions where pairs of participants were uni- and bi-directionally connected, in order to investigate the contribution of real-time responses from a partner during the interaction. Findings indicate similar improvements in tracking performance during the haptic conditions across joints, suggesting that uni-directional interaction is sufficient for movement correction during simple motor behaviors in healthy individuals.

1 Introduction

Humans physically interact to assist and learn from one another (e.g., during physical therapy). To study various aspects of human-human physical interaction, robotic systems can be used to render virtual haptic connections (e.g., spring-damper) between devices [1,4]. These upper- and lower-limb studies have shown that pairs of individuals perform tracking tasks better while connected compared to tracking alone; some studies have reported improved individual learning during these tasks as a result of dyadic training.

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The mechanism of improvements during human-human interaction is disputed, and likely depends on the task constraints (e.g., upper or lower limb, degrees of freedom). Previous work on upper-limb dyadic behaviors suggests that individuals consciously adapt their movement strategy in response to the haptic feedback received from their partner [2]. Our work in the lower limb suggests a mechanism for these improvements which is independent of adaptations in trajectory planning, where individuals improve through the mechanics of the connection to their partner [3].

It is unclear whether connected partners exhibit different behaviors when performing the same task with their upper or lower limb, and whether a change in mechanics is coordinated with a change in movement planning for either system. It is possible that individuals learn to regulate only their joint stiffness, not their trajectory, in response to the connection to their partner [4]. If the basis for this mechanism is mechanical and unrelated to motor planning, then changes in the movement strategy of each partner should have a limited effect on the resulting behavior. In this case, one would expect similar tracking improvements whether partners are connected uni- or bidirectionally.

Here we present results comparing dyadic behaviors during a trajectory tracking task for the upper and lower limb (i.e., wrist, ankle). We expect connected partners to improve similarly during wrist and ankle tasks according to their partner's ability, and that these improvements are explained by interaction mechanics. Our analysis focuses on changes in tracking error to assess improvements in performance as well as muscle co-contraction to represent changes in mechanics as a result of the connection. For the haptic conditions, we compare these measures between bi-directional connections where individuals are coupled to their partner in real-time and uni-directional connections where individuals are coupled to a recording of their partner's trajectory.

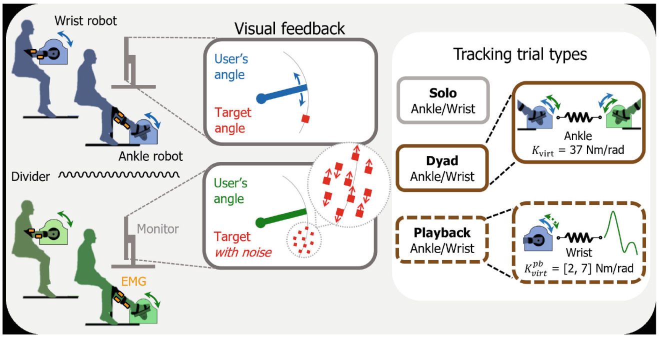

Fig. 1. Pairs tracked sinusoidal targets with visual feedback under different haptic conditions using either their wrist or ankle.

2 Methods and Materials

In our experiment, 4 pairs of healthy participants (dyads) used their wrists or ankles to perform 1-DoF movements while strapped into commercial robots (Fourier Intelligence, Singapore). The experiment consisted of two randomized phases, one for the wrist and ankle, and involved an electromyography (EMG) calibration followed by tracking trials. For the ankle, participants were restricted to dorsi- and plantarflexion; EMG sensors (Bagnoli, Delsys Inc., USA) were placed on the tibialis anterior and triceps surae. For the wrist, participants used flexion and extension; EMG sensors were placed on the extensor and flexor carpi radialis.

In tracking trials, dyads tried to match their wrist or ankle angle to a visually-displayed target while the robots were commanded with interaction torque control [3]. To vary partner differences, visual noise [4] was added to the target of one participant; the partner with noise was switched after a block of trials. The experiment consisted of 4 blocks, for each combination of noise and joint. In each block, dyads performed 5 solo trials where the ankle robots were transparent (i.e., near-zero interaction torque) and 10 haptic trials where a spring was rendered between the joint angles of each partner (Fig. 1). In the haptic dyad trials, real-time angles of each partner and a virtual stiffness ($K_{\text{virt}}^{\text{wrist}} = 3.7$ Nm/rad; $K_{\text{virt}}^{\text{ankle}} = 37$ Nm/rad) were used. In the haptic playback trials, participants were connected with the same stiffness to a recording of their partner's solo trial, accounting for the human stiffness element of each user [3].

For each joint and noise condition, improvements were measured by taking the normalized difference between solo and dyad or playback tracking errors [3],

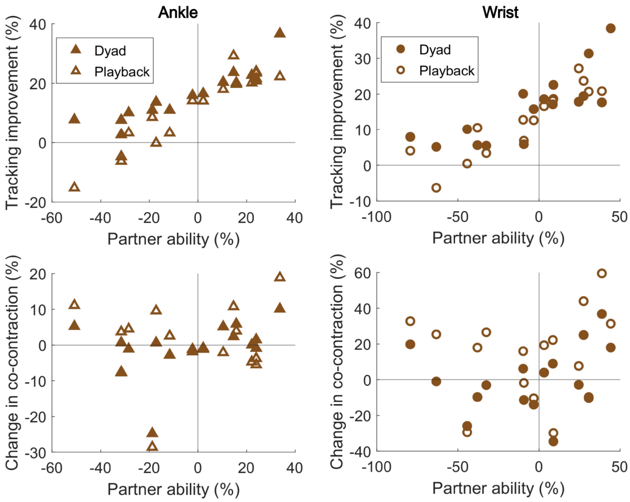

Fig. 2. Changes in tracking performance and co-contraction with and without haptic interaction, as a function of partner ability.

calculated as the root-mean-square error between the target and actual trajectories. Partner ability was measured by taking the normalized difference between the solo tracking errors of each partner in a dyad. After regressing EMG values with torques from an isometric calibration, co-contraction was computed by taking the minimum predicted torque between the antagonist-agonist pair during tracking trials. Changes in co-contraction were measured by taking the normalized difference between mean solo and dyad or playback co-contraction torques.

3 Results and Discussion

Figure 2 shows the relationship between each partner's ability and changes in performance and muscle activation during haptic interaction. For both the ankle and the wrist, similar trends in tracking improvement are apparent, as participants were able to track the targets more accurately during haptic interaction; this trend appears to be a 2^{nd} order polynomial, as the interaction particularly benefits the worse partner in the dyad (partner ability $> 0\%$). For the ankle, improvements in performance were slightly larger during the dyad condition compared to playback ($5.5 \pm 7.6\%$). For the wrist, improvements were more similar between the dyad and playback conditions ($1.8 \pm 6.0\%$). Similarities between the dyad and playback conditions may indicate that, particularly for a simple 1-DoF tracking task, the real-time response from a partner is not required in order to benefit from the interaction.

For both the wrist and ankle, co-contraction tended to increase near the bounds of partner ability. This could mean that partners who are very different (e.g., expert and novice) both tend to increase their joint stiffness, to resist the forces provided by their partner during the interaction. For the wrist, changes in co-contraction were larger during playback compared to the dyad condition ($-13.0 \pm 9.8\%$). This increase could highlight the enhanced ability of the upper-limb to detect and adapt to slight differences in the haptic conditions [4]. Because the playback trajectory acts independent of each partner during the interaction, it is likely that overall interaction torques were greater during this condition as participants did not continuously converge to the same angle. This could also explain the modest differences in dyad and playback improvements at the ankle, as participants did not exhibit the same adaptation in co-contraction ($1.2 \pm 5.5\%$) in order to appropriately resist the playback trajectories.

4 Conclusion

This study is a preliminary investigation in healthy individuals on dyadic behaviors in the upper and lower limb. We found that, for both the wrist and ankle, similar improvements in task performance could be achieved during either uni-directional or bi-directional interaction. During 1-DoF dyadic interaction, it is likely that each partner moves independently during the task and observed improvements are due to error averaging between partially correlated signals.

Future studies could involve simulation to characterize the contributions of mechanics and motor planning to dyadic behaviors. In addition, this work could be extended to patient populations (e.g., pairing physical therapists with patients post-stroke for ankle or wrist training) to examine the effects of haptic training in rehabilitation and whether or not bi-directional feedback is more significant in this context.

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