The Influence of Haptic Feedback and Visual Information on Multi-Limb Coordination

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***Abstract*—Multi-limb coordination is necessary for many daily activities. It also has particular relevance for a growing area of human-system applications such as teleoperated robot operation and supernumerary robot operation where an additional robotic limb may complement natural limb functions. Introducing supplemental sensory information, specifically haptic feedback, has shown the potential to improve assistive robotics control, human-machine interactions, and even human motor learning. However, there has been little research on how sensory information, including haptic feedback and visual information, contributes to the execution of multi-limb coordinated tasks. In this paper, we designed a tri-limb coordinated task where participants move a cursor to a randomly positioned target on a screen guided by variations of both haptic feedback and visual information. Our results indicated that while haptic feedback could partially substitute for visual information, it could not completely replace nor surpass the task performance achieved with visual information as feedback. Importantly, haptic feedback does not negatively impact performance metrics such as how often the participant coordinates multiple limbs simultaneously (coordination score), controls their limbs without redundant movement (normalized sub-optimal path), completes the task (success rate), and the mental workload perceived during the task (cognitive load). This study provides insight into the contribution of sensory feedback in facilitating multi-limb coordination, providing relevant guidance for numerous applications of human interactions with assistive technologies.**

***Index Terms*—human-machine interaction, multi-limb coordination, haptic vibration feedback, visual information**

I. Introduction

The ability of humans to control and coordinate multiple body parts simultaneously to effectively execute motor tasks has been a growing area of study across numerous fields (e.g., human motor control in healthy and sensorimotor impaired populations, cognitive neuroscience, assistive robotics, and human-machine interactions). Tasks ranging from simple activities like walking to more complex ones such as operating artificial limbs, driving a car, or playing a musical instrument often involve the coordination of multiple body parts to support and execute the requisite motor actions.

In these tasks, the brain integrates efferent motor commands with a rich stream of afferent sensory information from the body (reafference) and the environment (exafference) [1]. This process aids in developing internal models of the task and environment, adapting to perturbations, and converging on optimal strategies for coordinating movements and performing tasks [2]–[8]. From a control system's perspective, sensory information closes the motor control loop. However, in many assistive mechatronics, where effective operation requires coordination across the body, sensory feedback is not actively provided (e.g., prosthetic limb control interfaces, powered upper and lower limb exoskeletons, etc.) [9], [10].

The inclusion of supplemental sensory feedback, particularly haptic feedback, has the potential to enhance the execution of complex multi-limb tasks. This enhancement has been observed in various applications, including assistive systems for minimally invasive surgery, teleoperated robots, and collaborative tasks with supernumerary robots [11], [12]. Research suggests that haptic feedback can reduce excessive reliance on visual information and decrease cognitive load during demanding multi-limb tasks [13]–[16]. However, there is still a notable gap in our understanding of how visual and haptic information contribute and are integrated to facilitate these effects and improve performance. This is despite the extensive, existing literature on optimal sensory integration and task performance in single-limb or bimanual coordination [17], [18].

In this paper, we present the design and feasibility testing of an experimental platform developed to systematically manip-

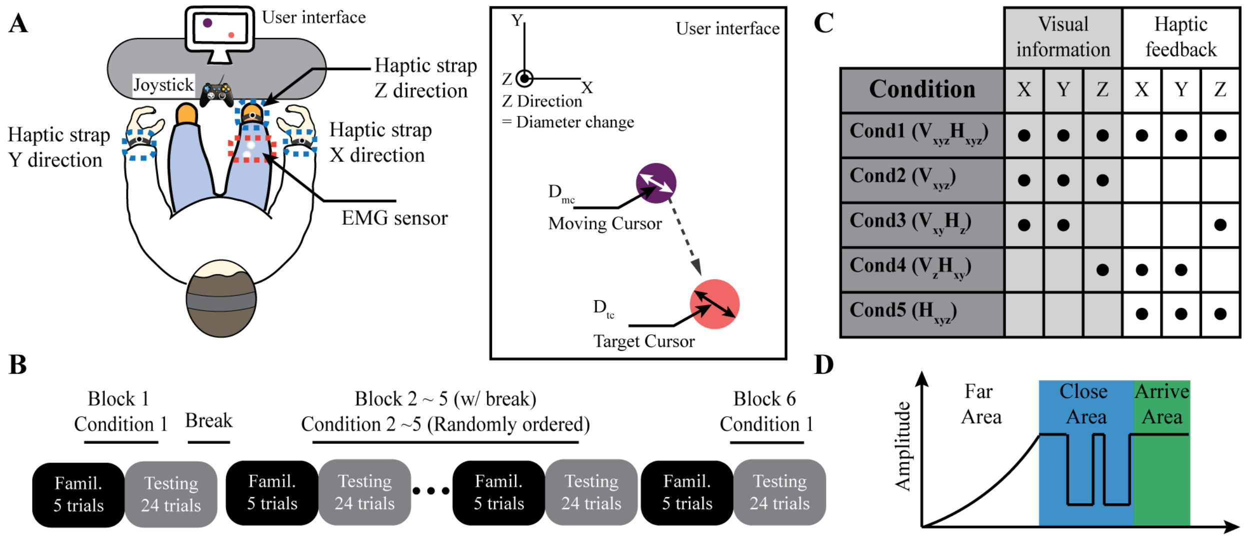

Fig. 1. (A) Schematic illustration of experimental setup for multi-limb coordinated task with the integration of variable haptic feedback and visual information (B) Experimental process consisting of six blocks with familiarization (5 trials) and testing session (24 trials) (C) Experimental conditions that vary the number of haptic feedback and visual information for each axis (D) The intensity change of vibration haptic feedback in accordance with the distance between current position of moving cursor and target cursor.

ulate haptic and visual feedback for participants performing a tri-limb coordinated task. The task involves moving a virtual cursor to a target across three degrees of freedom. Participants were required to manipulate the cursor using both hands (via a game controller) and an additional limb (leg with surface electromyography control, sEMG). We integrate a vibrotactile haptic feedback algorithm into this system, delivering task-relevant information to both hands and the leg. Through this setup, we demonstrate the sensitivity of our system in investigating the impact of haptic and visual feedback and its feasibility in determining how these two sensory channels are optimally integrated. Our system can help better understand how these feedback modalities influence performance in a tri-limb coordinated task and the extent to which they may help alleviate the cognitive load.

II. Method

A. Participants

A cohort of N=7 participants (57% male) was recruited. Testing was approved through UC Davis Institutional Review Board (IRB), and subjects provided informed consent before participating. Exclusion criteria consisted of history of neurological and neuromuscular disorders and limitations in hand or leg mobility.

B. Experimental Design

We designed a three-limb-controlled cursor-to-target task that is displayed on a computer monitor. The interface allows participants to control a cursor's movement in three dimensions (X, Y, and Z). Specifically, the cursor's movement in the X and Y directions were displayed as horizontal and vertical movements, and the radius of the cursor was adjusted to represent the movement in the Z direction (in and out of the screen). The experimental setup employed a way to manipulate a moving cursor to align with a target cursor in the X, Y, and Z directions using a joystick (Xbox controller) held with the participant's two hands and muscle activity controlled by surface electromyography (sEMG, CONMED electrodes) from the right leg, as illustrated in Fig.1A. These electrode pairs were placed on the anterior tibialis tendon and posterior gastrocnemius muscles of participants' right legs. sEMG signals from differential electrode pairs were sampled at a frequency of 2048Hz using the MCC data acquisition system (USB-1608G, Measurement Computing).

Acquired sEMG cursor control signals, filtered in real-time using a Butterworth bandpass filter (4^{th}order,10 Hz to 500Hz), were processed using the Teager-Kaiser Energy Operator formula to identify the onset of muscle activity. For each muscle site, activation thresholds were established based on the mean and standard deviations of signals recorded during subjects' muscle flexion. Activation thresholds were defined as the mean of a signal plus four times the standard deviation. When muscle activity surpassed the activation thresholds, the cursor's movement in the respective axes was activated.

The control mapping scheme assigned movement in the X direction (left/right) to the right hand, the Y direction (up/down) to the left hand, and the Z direction (cursor radius increase/decrease) to the right leg. Also, the experimental setup incorporated three custom haptic vibration straps that utilized eccentric mass vibration motors. They provided information relating to the X, Y, and Z distance of the cursor from the target position by providing vibration to the corresponding limb controlling that movement in that direction. We encoded the distance by dividing each axis of movement (X, Y, and Z) on the 2D plane into three distinct regions and provided distinct vibration patterns for each region as follows: "far region",

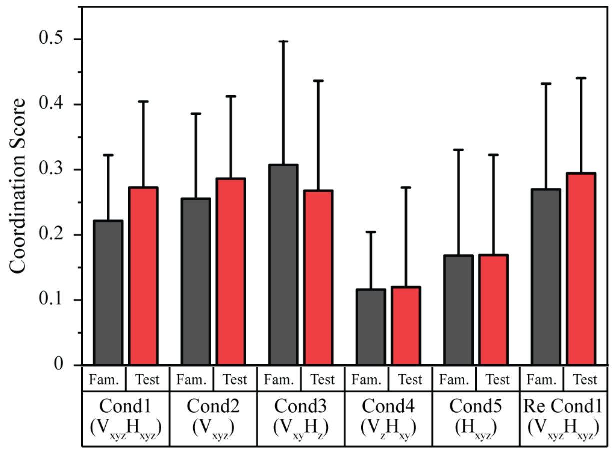

Fig. 2. Coordination score, how often participants use their limbs together within each trial according to each condition.

defined as the distance greater than three times the target radius (D_{tc}), "close region", defined as the distance greater than $0.5D_{tc}$ and less than $3D_{tc}$, and "arrive region", defined as the distance less than $0.5D_{tc}$. Vibration amplitude increased when the moving cursor approached the target position ("far region"), followed by a pulse-width-modulation (PWM) like the "ON/OFF" pattern ("close region"). Lastly, a sustained maximum vibration intensity was maintained to notify that the moving cursor is within the "arrive region", as illustrated in Fig.1D.

In the tri-limb coordinated task, participants were instructed to control the cursor's movement in three dimensions fastly while trying to use their limbs simultaneously. The experiment was comprised of six blocks, consisting of five familiarization trials and twenty-four testing trials (Fig.1B). In each trial, the position and radius of the target cursor were pseudo-randomized among 24 possible target locations. Participants were provided with both visual and haptic vibration feedback for all directions (X, Y, and Z) at the beginning and end of this experiment (Block 1 and Block 6). In the between blocks, they were provided with randomly ordered sensory feedback conditions which included different combinations of haptic and visual information related to the movement in each axis (X-Y-Z direction), as described in Fig.1C.

III. Data Analysis and Results

We evaluated task performance through three main metrics: coordination score, normalized suboptimal path, and success rate. Additionally, to assess cognitive load during the task, subjective perceptions of the task's difficulty and demand were measured using a 10-scaled Modified Bedford workload [19]. The coordination score was computed as the ratio of time spent moving at least two limbs together to the total duration of each trial they performed within the "trial timed-out" time duration (30 seconds). The normalized suboptimal path was determined by subtracting the actual cursor path length from the optimal path length along each direction and dividing the result by the total optimal path length. This optimal path length was defined as the shortest Euclidean length required for the moving cursor to reach the target position from its starting position in each degree of freedom. Additionally, a successful trial was considered when the final position of the moving cursor was within a distance of $\sqrt{101}$ pixel units from the target position within the "trial timed-out" time duration. Then, the success rate was evaluated by calculating the ratio of the number of successful trials to the total number of trials conducted during the testing session. Lastly, participants rated their cognitive workload using a three-rank ordinal structure that ranges from 1 to 10, where 1 indicates the lowest workload and 10 indicates the highest workload for each block.

A. Coordination Score

The data (Fig.2) suggests that there was minimal to no discernible difference between conditions when haptic vibration feedback was provided in addition to visual information for all axes (Cond1 and Re Cond1) when compared to visual information alone (Cond2). Also, we found that when haptic vibration feedback was substituted for visual information in two or more axes (Cond4 and Cond5), it led to a decrease in the coordination score. However, when participants were provided with haptic vibration feedback for only one axis of movement along with visual information for the other 2 axes (Cond3), they maintained coordination scores similar to those seen when visual information was provided for all axes (Fig.2).

B. Normalized Sub-optimal Path

The normalized sub-optimal path quantified the degree to which redundant cursor movements were present (leading to a higher difference between actual and optimal path length in each axis movement). We observed higher values (more redundancy) of the normalized sub-optimal path when haptic feedback was substituted for visual information in two or more axes of control (Cond4 and Cond5). However, when haptic vibration feedback was substituted for visual information for

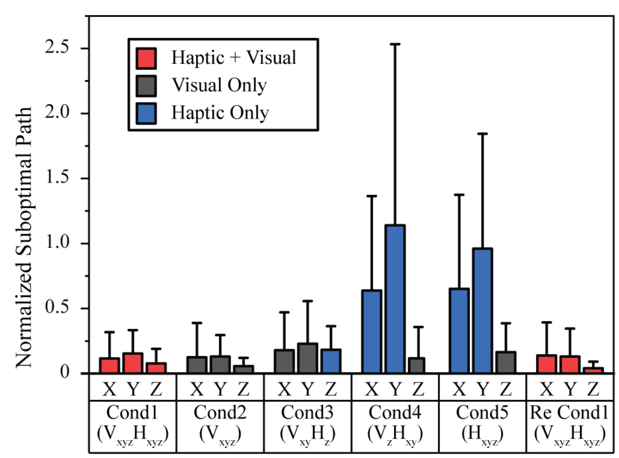

Fig. 3. Normalized suboptimal path illustrating the comparison of path length between the optimal and the actual trajectory. A value closer to 0 denotes that the cursor follows the optimal pathway, representing the shortest distance to navigate it to the target position along each axis.

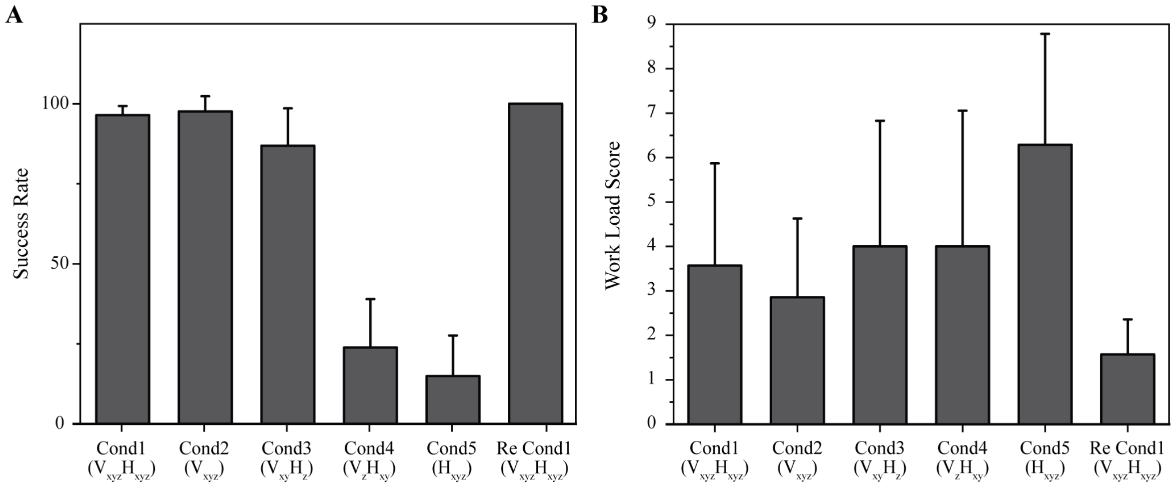

Fig. 4. (A) Average of success rate and (B) Average of cognitive load during the testing session for each combination of haptic vibration feedback and visual information.

a single axis of movement, subjects placed the cursor in the target position along the Z axis with less redundant control, as captured in the lower normalized sub-optimal path (Fig.3).

C. Success Rate and Cognitive Load

To investigate the impact of haptic feedback and visual information on cognitive load, we implemented the modified Bedford workload scale, a subjective assessment of the task's difficulty. When participants encountered the first block with haptic feedback and visual information for all axes of cursor movement (Cond1), their cognitive load was slightly higher compared to when they repeated the task with the same condition (Re Cond1) or when they only had visual information (Cond2). Additionally, when haptic feedback was partially substituted for visual information (Cond3 and Cond4), workload scores appeared to increase with the maximum effect of this being seen when the participant solely relied on haptic feedback alone (Cond5). Finally, repeating the task with visual information and haptic feedback for three degrees of freedom (Re Cond1) resulted in the participants' perception of the task load being less demanding.

In the success rate measurement, the trends were similar to other performance measurements (coordination score and normalized sub-optimal path). Specifically, we found that if the haptic feedback was provided for more axes than visual information, this resulted in a decrease in the success rate. This was contrary to when one axis movement was guided solely by haptic feedback, which appeared to have minimal effect on the success rate compared to when haptic feedback surpassed visual information (Fig.4).

IV. Discussion and Conclusions

When examining how individuals perform tasks displayed on the computer monitor involving multiple limbs, and manipulating the haptic feedback and visual information they receive, we can provide valuable insights into their motor behaviors. By analyzing both objective measures and subjective data, we can better understand how haptic vibration feedback and visual information influence coordination among multiple limbs.

The objective task performance matrices including coordination score, normalized sub-optimal path, and success rate suggest that the absence of visual information for at least two axes of cursor movement detrimentally affected the coordination of multiple limbs together. However, when visual information was not present in only one direction of cursor movement (Z-axis), our findings demonstrated that haptic vibration feedback may substitute for visual information without compromising coordination or task performance (Fig.2 and Fig.3)

In cursor-to-target tasks requiring multi-limb coordination, redundant control is characterized as the deviation from an optimal trajectory in each direction, which we termed normalized sub-optimal movement. In the normalized sub-optimal movement results, participants demonstrated redundant movements when lacking visual information on more than one axis. However, when visual information was removed for the axis of cursor movement controlled by sEMG, there was minimal deviation for the optimal path in acquiring the target. This is a surprising result given the novelty of a sEMG control scheme to a naive participant, compared to the more common joystick control utilized for other axes of movement. This finding may imply that haptic vibration feedback may provide benefits for learning new, novel control schemes, compared to familiar control schemes in which haptic feedback may serve no additional use, or even impair performance (results from Con4 and Con5 in Fig.2 and Fig.3).

In the assessment of task success rate, we demonstrate that the results are aligned with other objective task performance metrics - coordination score and normalized sub-optimal path. Specifically, our findings suggest that haptic vibration feedback may have the potential to overwhelm the user when compared to visual information. However, when substituting the haptic vibration feedback for visual information along one axis, minimal impact on the success rate was found. This is further supported by cognitive workload results (modified Bedford workload scale), in which participants appeared to report higher workloads when haptic information was used to direct cursor movement in more than one axis. Conversely, when participants were offered both haptic vibration feedback and visual information across all axes (Re Cond1), they exhibited increased task performance with reduced perceived workload (Fig.4).

When taken together, our findings demonstrate that visual information may dominate over haptic feedback during multi-limb cursor-to-target tasks; however, haptic feedback can substitute for some (but not all) visual information with minimal decrements in the coordination of limbs, the optimal cursor control without redundant movement, the success rate, and the cognitive load. Our observations are supported by previous research suggesting that concurrent visual feedback facilitates rapid access to task-specific information, which might be required for controlling at least two limbs together [20], [21].

Our findings provide encouraging data for follow-on work in larger cohorts of participants such that statistical power and detailed analysis can be performed to more conclusively interrogate the nature of the relationships between haptic feedback and visual information using our multi-limb coordination paradigm. Furthermore, it is important to note that the control mapping scheme, how each limb (left hand, right hand, and foot) is allocated to control different degrees of freedom along the X, Y, and Z axes, may potentially impact the execution of tri-limb coordinated tasks. Future work will investigate the contribution of haptic feedback and visual information to tri-limb coordinated tasks and the role different limbs and control schemes may play. Despite these untested variations, our work provides a viable experimental paradigm and early encouraging insight into the simultaneous control of multiple limbs during human-machine interactions. Furthermore, investigating the extent to which haptic feedback can influence multi-limb coordination task performance could allow us to design an optimal integration strategy for haptic feedback interfaces in systems where visual information could be partially or fully substituted by haptic inputs. This understanding is crucial for the design of feedback interfaces in various applications, such as teleoperate robotic operations, surgical robots, and supernumerary robots for assistive tasks. Such integration could significantly improve user interaction by aligning the sensory modalities involved, thereby enhancing the overall system performance and user experience.

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