Learning How to Use a Supernumerary Thumb

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Abstract: This study presents a novel system consisting of a supernumerary robotic thumb and a virtual reality-based mirror paradigm in a leader-follower mode. As the extra thumb skeleton, a planar robotic mechanism with two degrees of freedom is utilized. The experimental setup poses the task of acquiring proficiency in controlling the supernumerary second thumb throughout a five-day duration of engaging in the leader-follower game. There is evidence that after five days of practice, a subject's motor performance improves and motor variability decreases.

1 INTRODUCTION

Supernumerary Robotic Limbs (SRLs) are at the forefront of human-robot cooperation and integration research. They are designed to increase job efficiency and safety, augment different human body functions, and restore certain capabilities for persons with disabilities (Yang et al., 2021; Tong & Liu, 2021). Supernumerary limbs include robotic arms, robotic legs, and supernumerary robotic fingers (SRFs). Supernumerary robotic fingers are often intended to serve two functions. The aforementioned goals are to supplement a healthy person's hand (Ariyanto et al., 2017; Hussain et al., 2017) or to compensate for lost functions caused by severe disorders like strokes (Salvietti et al., 2021; Lee et al., 2021). The majority of supernumerary robotic fingers are meant to aid in the grasping of daily objects, while some are aimed to better a human-performed task, such as playing the piano (Cunningham et al., 2018). The potential applications of a supernumerary robotic finger design may be constrained in comparison to other forms of supernumerary robotic limbs, primarily due to limitations imposed by size and weight considerations. Most supernumerary robotic fingers are designed with specialization in mind, focusing on the accomplishment of a singular task, such as grasping.

The objective of this study is to establish a framework for examining the enhancement of manual dexterity in healthy individuals through the utilization of a robotic supplementary thumb as an additional appendage. We considered a scenario in which, instead of using the original thumb to push or compress an elastic object, a supernumerary robotic thumb is employed to execute the same action. In the meanwhile, the original thumb is utilized to manipulate a joystick. The proposed novel system combines SRF with a virtual reality-based leader-follower game. The interaction force due to the compression of the spring is utilized in the virtual reality environment to make the follower's avatar track the leader. While following the leader, the subject is instructed to shoot a laser gun at a target on the leader in order to score points by manipulating the joystick. The game was played by a participant on a daily basis, completing 15 rounds each day for a consecutive period of 5 days. The performance was analyzed within the context of motor learning. The score attained during the phases of habituation, learning, and retention are used to characterize motor learning. Additionally, motor variability is used to assess motor learning.

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2 EXPERIMENTAL SYSTEM

The experimental system is developed to study how we learn to utilize the supernumerary thumb while playing a virtual reality-based leader-follower game. Figure 1 shows the components of the system and Figure 2 illustrates typical data monitoring during the rounds. For each round, the pedal and button force inputs, joystick firing inputs, leader and follower positions, and scores are all recorded. The system's components are discussed in the following sections.

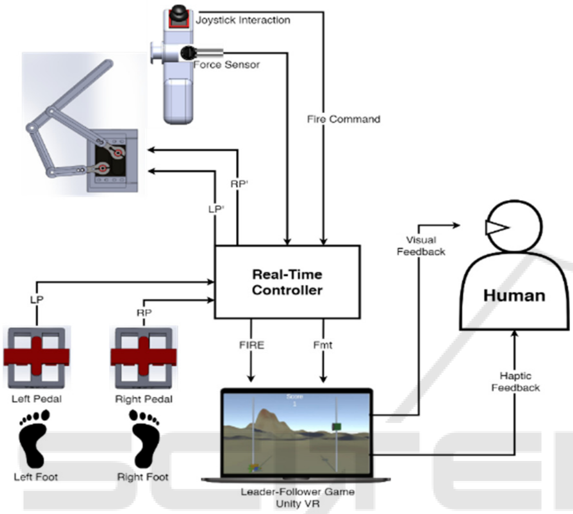

Figure 1: Overall system architecture.

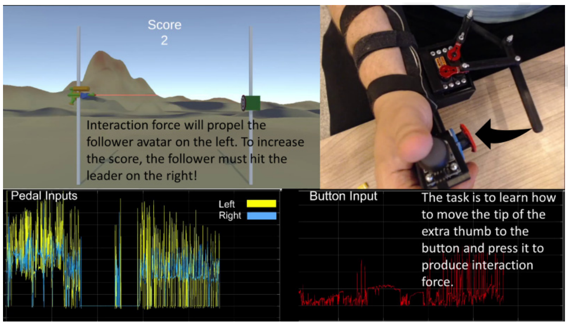

Figure 2: Screen shots of a typical round.

2.1 Two Degrees of Freedom (DOF) Robotic Thumb

The chosen topology for the supernumerary thumb is a 2 degree-of-freedom planar robot arm, as depicted in Figure 3. The mechanism offers alternative learning opportunities by presenting challenges in both task space and joint space mapping of pedal inputs. The selection of working space is undertaken to uncover potential avenues for exploration during the training process, Figure 4. Determining link lengths is achieved through simulations that aim to reach the desired exploration space while considering feasible transmission angles. Transmission angles are necessary for maintaining the desired interaction forces, such as when exerting pressure on the red button.

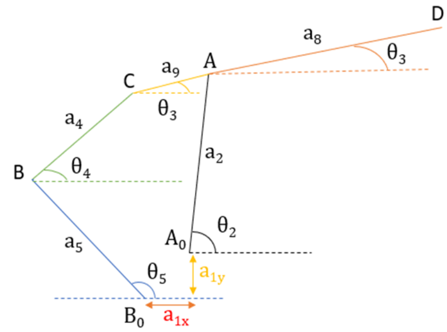

Figure 3: Two degrees of freedom planar mechanism as the second thumb mechanism.

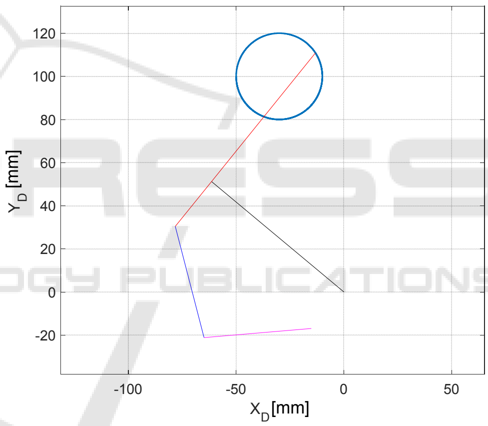

Figure 4: Screen shot from the kinematic animation of the mechanism tracing a circular path in workspace. Tip of the mechanism is point D.

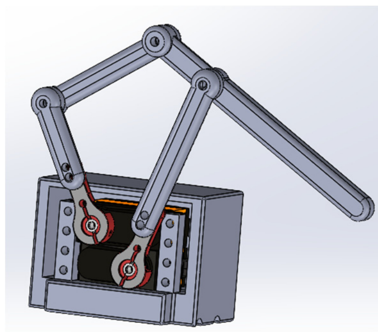

Figure 5: Solid model of the synthesized mechanism with the actuators.

2.2 Hand Interface and Pedals

The objective of this study is to acquire the skill of pressing the red buttons depicted in Figures 2 and 6 using the supernumerary thumb. This action will result in the generation of an interaction force, which is produced by compressing a linear spring. The force sensor detects the generated interaction force, which is then processed by the microcontroller board. In the game, the follower avatar utilizes it as a means of generating upward propulsion. Furthermore, the input is transformed into a linear mapping that is then converted into a pulse width modulated (PWM) signal. This signal is subsequently utilized to drive a vibrating motor, which in turn delivers haptic feedback to the player's wrist.

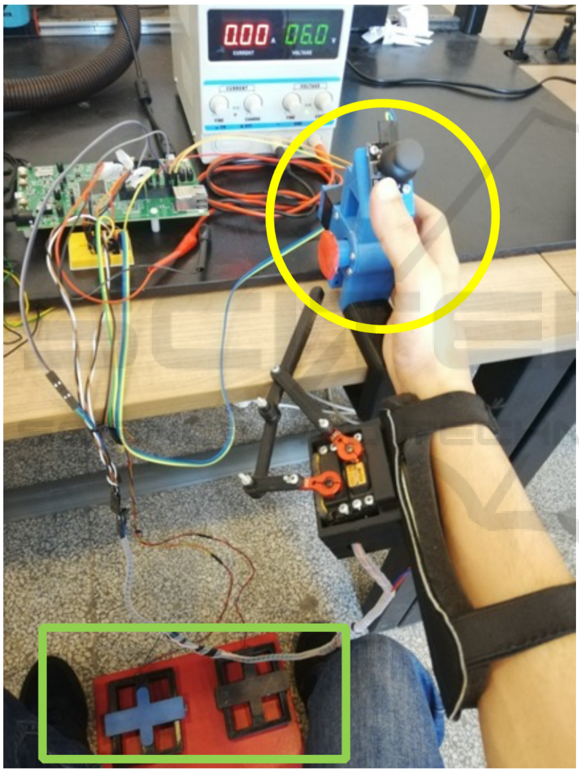

Figure 6: Pinching interface (in yellow circle) and pedals (in green rectangle).

The experimental setup that has been developed consists of two pedals, one for the left foot and another for the right foot, as depicted in Figure 6. A force sensor, specifically a force-sensing resistor, is installed on each pedal. To address the issue of parasitic noise originating from the lengthy 1.5-meter wires connecting the sensors to the pedals, as well as for signal conditioning purposes, an operational amplifier (op-amp) is employed in a voltage-follower configuration. This configuration is placed between each sensor and its corresponding analog-to-digital converter (ADC) input. The microcontroller employs a linear mapping technique to convert pedal forces into two pulse width modulation (PWM) signals. These signals serve as reference position inputs for the two mini servomotors that drive the two degrees of freedom (2-DOF) thumb mechanism, as shown in Figure 5. The position control systems that are inherently present within the RC-servo motors are exclusively employed.

2.3 Real-Time Control System

In this study, i.MX RT1024-EVK microcontroller board is used as the real-time control hardware, Figure 7.

Figure 7: Real-time control hardware.

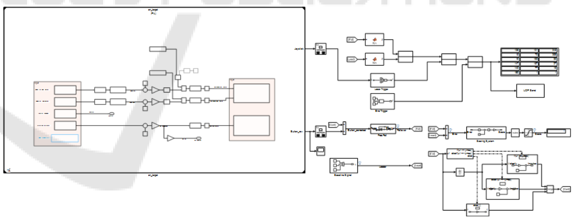

Figure 8: Real-time control system built in Simulink and runnig on MXP board – part 1 on the left, part 2 on the right.

The software architecture for this project has been developed using MATLAB/Simulink. The system can be conceptually separated into two primary components: (1) the module responsible for acquiring data and transmitting actuation signals to and from the external environment, and (2) the module that executes game control algorithms and manages the physics of the system, as depicted in Figure 8.

The first part utilizes the MBDT toolbox, providing access to the peripherals of the i.MX RT1024-EVK, a robust microcontroller board operating at a frequency of 500MHz. This board is capable of supporting real-time scheduling. The ADC

(Analog-Digital Converter) blocks and PWM (Pulse Width Modulation) blocks were utilized to successfully interface with the sensors and control the actuation process. The connection between the two stages of blocks is facilitated by a pipeline consisting of commonly used Simulink gain, bias, numerical filter, and saturation blocks. It is important to acknowledge that the determination of the values in these blocks was primarily based on empirical methods, taking into consideration the mechanical limitations of the servo motors. Significantly, every MBDT block offers a means of accessing MCUXpresso Config, an independent software tool designed for the purpose of advanced configuration of the peripherals of i.MX RT1024-EVK. It is at this stage that we can configure the ADC resolutions, PWM frequency, initial duty cycle, pin assignments, and various other parameters that pertain to the low-level layer of the microcontroller.

The subsequent component of our architectural design is responsible for managing the underlying principles that dictate the dynamics of the "leader-follower" game. This includes the application of Newtonian mechanics, the establishment of scoring mechanisms, the implementation of a "leader" signal, the establishment of boundaries, and the enforcement of a time limit of 90 seconds for each iteration. The aforementioned values are encoded and parsed into packets, which are subsequently transmitted over the User Datagram Protocol (UDP) to an IP address. This IP address corresponds to the location where the "leader-follower" game is actively listening. It is important to note that this game, developed using the Unity engine, operates concurrently on a distinct instance that is external to MATLAB. The initial component of the architecture, which is solely concerned with sensing and actuating, operates at a sampling frequency of 100 Hz. However, the subsequent component responsible for executing intricate algorithms operates at a higher frequency of 1 KHz.

The initial segment is executed on the microcontroller board depicted in Figure 7, while the subsequent segment is executed on the primary computer that hosts MATLAB. The utilization of the PIL (Processor-in-the-Loop) framework of the i.MX RT1024-EVK board enables the achievement of this capability. It is considered the recommended approach for co-simulation of this nature, wherein each processing platform assumes responsibility for its respective native blocks.

2.4 Leader-Follower Game

The mirror paradigm's leader-follower modality is implemented within a game format, utilizing the Unity engine. The leader, equipped with a target pane, is executing a uniaxial motion in both the upward and downward directions. The objective of the follower positioned on the left is to consistently track the movements of the leader and skilfully engage the target by discharging the laser weapon, thereby acquiring points. Figure 10 presents a screenshot from the implementation.

The leader's motion is made up of the sum of three sine waves, which provides a complex reference for the follower. However, such references have been proven in the literature to be implicitly learned (Pew, 1974; Polat, 2022).

The force resulting from the interaction between the second thumb and the button in the hand interface is utilized as the vertical force for propelling the avatar of the follower in an upward direction. In order to induce downward movement of the avatar, it is necessary to decrease the interaction force to a magnitude that is lower than the weight of the avatar. This reduction in force will generate a net force in the negative y direction.

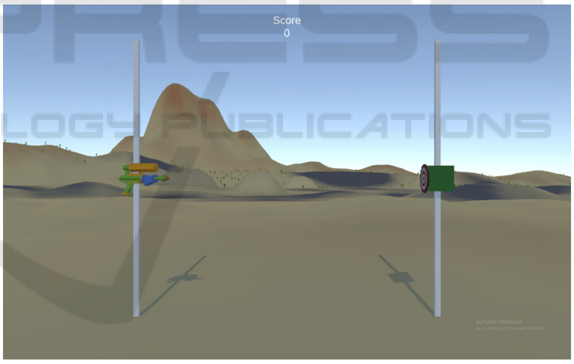

Figure 9: Leader-follower game in Unity.

2.5 Experimental Protocol

The participant, a 23-year-old male, was instructed to complete the game challenge in the conventional manner, excluding the use of the sixth finger, and instead utilizing their own thumb. Then, the individual puts on the robotic extra thumb on their right hand and engages in the game as a daily regimen consisting of 15 rounds, each lasting 90 seconds, over a span of 5 consecutive days.

On a daily basis, the experimental procedure consisted of a series of rounds. For each day, the initial 2 rounds were designated as habituation runs, followed by 11 rounds of learning trials, and concluding with 2 rounds specifically designed as retention runs. The leader's pattern is the same throughout the habituation and retention rounds. During the training sessions, the leader moved in the habituation pattern's mirror symmetry.

3 RESULTS AND DISCUSSION

The score of the subject is presented in Figure 11. The black bar shows the performance without extra robotic limb.

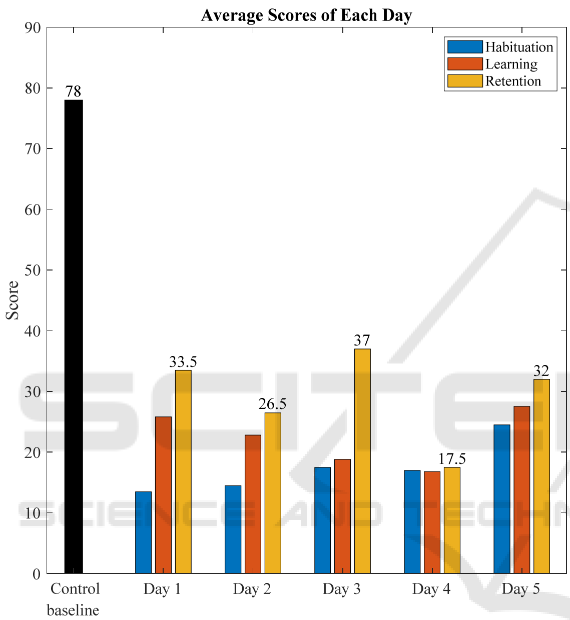

Figure 10: Average scores.

Daily, the subject's performance improves when the scores of the habituation and retention trials are compared. When the habituation scores of all sessions are compared, there is a positive trend. However, when learning and retention performance for the whole experimental time is examined, we do not detect a comparable tendency. As a result, it is difficult to claim that a skill can be learned in 5 days of training.

Additionally, we examined the motor variability of the supernumerary thumb control. During motor learning, it is known that the exploration phase must be diminished, and the exploitation phase must be prolonged. This reduces the motor variability of the subject's control action (Dhawale et al., 2017). We discussed the trajectory of the tip point D of the robotic thumb mechanism to evaluate the motor variability. The trajectories observed during the final round of training on the first and fifth days are shown in Figure 12. When the trajectories are compared, the reduced motor variability is interpreted as a sign of motor learning progress.

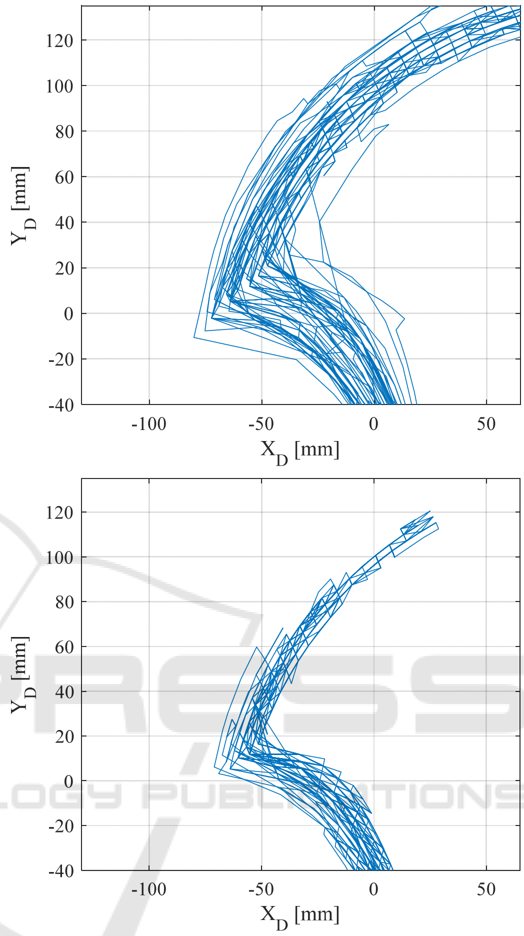

Figure 11: Trajectories of point D – Top: Last round of day 1, Bottom: Last round of day 5.

4 CONCLUSIONS

A novel system has been developed to investigate the process of motor learning during practice involving the control of a supernumerary second thumb. The setup allows for the investigation of learning in either the joint or task space of the supernumerary limb. Further research will investigate the variations in retention and transfer of motor learning that correspond to the learning spaces.

In this study, the motor learning task can be categorized into various regimens. The initial subtask involves positioning the robotic finger's tip in proximity to the red button. Subsequently, the finger must acquire the capability to apply force to the button to propel the avatar in the game. Lastly, the finger must possess the ability to anticipate the movements of the leader in order to effectively pursue the leader avatar. In addition, it is imperative to acquire the skill of accumulating points via the act of firing the laser beam by utilizing the organic thumb in conjunction with the robotic thumb. Hence, the experimental system can be utilized to investigate diverse characteristics of motor learning. It is important to assess the motor performance in each phase separately as well.

For the first regime, where it is learned to navigate the robotic finger's tip from its initial position to the button location, motor performance increases over repeated rounds. Motor variability in this phase is reduced as shown in Figure 12. Nevertheless, there is criticism regarding the necessity for additional rounds and extended periods of time to acquire proficiency to accumulate scores as following the leader avatar. This inquiry serves as the central focus of our ongoing research, namely, the investigation into the methods by which motor learning can be facilitated or enhanced. This study demonstrates the fundamental integration of a robotic finger and a virtual reality system using the mirror paradigm. The subsequent stage involves the development of shared control architectures with the aim of facilitating motor learning. Furthermore, the utilization of force fields, haptic interaction, and disturbances will be employed to augment the process of motor learning (Özen et al., 2021; Brookes et al., 2020). In addition to the kinematic and kinetic data, neuroplasticity will be evaluated by processing the EEG data. To evaluate motor learning concretely, nonlinear measures will be used.

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