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Foot-Controlled Supernumerary Robotic Arm: Foot Interfaces and Human Abilities

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Foot-Controlled Supernumerary Robotic Arm:

Foot Interfaces and Human Abilities

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ABSTRACT

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Foot-Controlled Supernumerary Robotic Arm: Foot Interfaces and Human Abilities

Thesis Advisor: Dr. Ryder Winck

A supernumerary robotic limb (SRL) is a robotic limb that can act as an extra arm or leg for a human user. An unsolved issue with SRLs is how to operate them well. One possibility is to control an SRL with the foot, which offers the benefit of a third arm because the user's arms remain unoccupied. While hand interfaces are common, foot interfaces are not well understood. Developing a good foot interface is challenging because of differences between feet and hands, such as the larger inertia of the leg. This thesis presents work to determine some design principles for foot interfaces. First, an experiment is done to test if the addition of friction to a foot interface can improve performance. The results show that friction can help a user stop and hold position without reducing the dynamic performance of the user. A second experiment looks at the performance of isometric interfaces, which, unlike isotonic interfaces, use force inputs rather than motion. Isotonic interfaces generally outperformed isometric, although there were only small differences between rate control for both isotonic and isometric. Additionally, rate control was found to be better than position control for the isometric interface. Finally, an experiment was conducted to evaluate how well a human user can use a foot-controlled SRL to coordinate motion with both of their hands. People showed that they could reliably use their foot in conjunction with their hands to perform a two-dimensional positioning task better than they can with just two hands, and with performance resembling that of two human users.

Keywords: supernumerary robotic limbs, foot control, robotics, teleoperation

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SRL	Supernumerary Robotic Limb
DOF	Degrees of Freedom
TLX	Task Load Index
ITP	Isotonic Position
ITR	Isotonic Rate
IMP	Isometric Position
IMR	Isometric Rate

GLOSSARY

Supernumerary Robotic Limb – A robotic arm that functions as an additional limb for a user

Extrinsic Sensing – Method of sensing that uses devices placed in the environment to record the operator

Intrinsic Sensing – Method of sensing that uses devices attached to the operator

Mediated Sensing – Method of sensing that requires the operator to act on a physical device

Isotonic – Dynamic, requiring movement inputs

Isometric – Stationary, requiring force inputs

1. INTRODUCTION

Supernumerary robotic limbs (SRLs) are robots that assist human users with accomplishing a task by providing the user with an extra limb. The potential benefits of SRLs are well understood. SRLs have been shown to increase productivity [1], and they have shown potential to be used to help with tasks such as surgery [2], aircraft assembly [1], and everyday activities [3]. Vatsal and Hoffman describe several situations in which an extra robotic limb is beneficial, such as stabilizing a drill, holding a circuit board while soldering, or handling hot objects [4]. One of the unsolved challenges surrounding SRLs is how to best control them. For an SRL to be useful it needs to be intuitive to control, otherwise the benefits that come with it could be reduced, or performance could even be hindered due to the added cognitive load.

There are two types of robot control that have been explored with SRLs: direct control [1, 4], and autonomous control [2]. Direct control, or teleoperation lets a user directly control a robot with an interface such as a joystick. Autonomous control needs little to no input from the user, but the robot must know what the user is doing, identify their intent, and decide on the best way to assist the user. Autonomous control is better suited to repetitive tasks because it is more feasible to infer the actions of the user [1]. Teleoperation is normally done via a hand interface and is advantageous because it removes the need for the robot to interpret the user's intent. Although a hand interface is intuitive, it occupies at least one of the user's hands that could be used to do other tasks. Several researchers have recommended the use of a foot interface for robotic arms [2, 3, 5]. Controlling the robot with the foot offers the benefit of a third arm since the user's hands would not need to control the robot. Additionally, because the user is directly controlling the robot, it can operate without the difficulties that come with autonomous control. This thesis focuses on foot control because it provides the benefits of direct control while leaving the user's arms and hands unoccupied.

Past research on foot interfaces has revealed elements of the design that need improvement. Past work with foot interfaces featured interfaces that needed relatively large translations of the foot and leg, which noticeably fatigued users after extended use [7]. Reducing the necessary motion of the foot and leg would reduce the fatigue experienced by users. One way this can be accomplished is by limiting the foot to using rotation instead of translation. The interfaces presented in this thesis are designed to use little to no translation of the foot.

The planar interface presented by Dougherty showed that position control was better than rate control for the foot, but it was not as good at stopping at a target [7]. Adding friction to a foot interface with position control could help improve the stopping behavior of position control, and it would allow the user to remove their foot without affecting the input, another advantage that rate had over position. Conventional wisdom in foot interface design is to remove friction because it removes resistance from the interface. No study has been done to evaluate the effects of friction on a control interface, either for hand or foot.

This thesis presents a comparison of a position control foot interface both with and without friction. A position control interface with two rotational degrees of freedom was designed, and friction could be easily added or removed. The interface, both with and without friction, was used in an experiment where subjects completed a time-critical reaching task and an accuracy-critical path-following task. The tasks evaluated how well a user could reach points quickly and how well they could make fine adjustments. Friction showed a statistically significant improvement in performance, so the subsequent research with position control featured the interface with added friction.

Subjects in the friction experiment experienced less fatigue when they had to move their foot less. The amount of fatigue was based on the survey results of physical demand and required effort. Because removing the need for motion could further reduce fatigue, a new interface was developed that needed no movement at all, either in translation or rotation. There are two kinds of input for a control interface: isotonic and isometric. An isotonic device is moved/manipulated by the user to change the output, such as the one in the first experiment, whereas an isometric device does not move, and instead reads forces, torques, or some other input which does not require movement. Although an isotonic interface with friction was found to be intuitive and perform well, a potential drawback of isotonic interfaces is that even the small movement necessary to use the interface can fatigue the user after extended periods of time. The lack of motion needed for an isometric interface may prove them to be less fatiguing than an isotonic interface because users would not need to move their legs, which have significantly more inertia than arms. An isometric interface can still make use of larger leg muscles and has the added benefit of being easily adaptable to higher DOFs. There is a lack of research investigating isometric foot interfaces, so this thesis presents and evaluates an isometric interface.

This thesis presents a comparison of the performances of isometric interfaces. An isometric interface was developed that could be used for position and rate control via a 6-axis force/torque sensor. The performances of the isometric interface using position and rate control were evaluated and compared using the reaching and path-following tasks that were used in the friction experiment. The isometric performance was also compared to the performance of isotonic interfaces. Unlike the isotonic interfaces, rate control was better than position control.

Isometric rate control was comparable to isotonic rate control, so depending on the application, either interface could be used effectively. Isotonic position control was the overall best performing interface.

A drawback of foot interfaces is that people are not as accustomed to performing dexterous tasks with their foot. Using the feet in combination with the hands is already common, like playing musical instruments or driving a car, but the role of the foot in these tasks is relatively simple. It is not entirely clear whether or not people can reliably use a robotic third arm in conjunction with their hands, so an experiment was designed to investigate this question. The experiment was developed to evaluate how well people can coordinate hand motion with a foot-controlled robot, and it involved a task in which subjects had to use their hands and foot to follow a path. The isotonic foot interface with friction was connected to a Sawyer robot so that subjects could control it with position control. Robot assistance resulted in a statistically significant improvement in completion time compared to solo performance. The performance of a human with robot assistance was statistically indistinguishable from the performance of two human users, and it was significantly better than the performance of a solo human user. As the task increased in difficulty, robot-assisted performance approached the performance of two users.

This thesis presents the existing background research for supernumerary robotic limbs and foot control for robots in Section 2. Three experiments with foot interfaces are described. The friction experiment is in Section 3, the isotonic and isometric comparison is in Section 4, and the foot-controlled SRL experiment is in Section 5. The conclusions from the experiments are presented in section 6, and possible future work is discussed in section 7.

2. LITERATURE REVIEW

2.1. Supernumerary Robotic Limbs

Access to a supernumerary robotic limb (SRL) can increase worker productivity and efficiency. One such example is aircraft assembly as explained by Parietti and Asada [1], where the necessary number of workers and effort to complete the task is significantly reduced. Another example is robot-assisted surgery, as explained by Abdi et al.[7], where the surgeon can control a camera to follow their hands, reducing the need for extra assistants. SRLs are not restricted to arms; they can also come in the form of supporting arms to help users with work that is low to the ground, effectively providing extra legs [9], or even fingers to help grasp objects [10].

Research on foot-controlled SRLs has been done by Sasaki et al., in which the user's leg motions are mapped to a pair of robotic arms that are mounted to the user's back [3]. The extra two limbs assisted the user with things like holding objects or soldering, although there is scarce information regarding the performance of the arms. Parietti and Asada also showed how body-mounted robotic arms could help with industrial assembly tasks [1]. Additional research by Vatsal and Hoffman showed a variety of applications that are easier with assistance from a robotic forearm [4]. Even an SRL as simple as an extra finger has been shown to assist users [10].

SRLs have been defined as a robotic limb that is worn by the user [11]. However, SRLs do not need to be worn to provide a benefit to the user. They can offer a similar level of assistance by simply being in the same workspace. Abdi has shown that a virtual arm can be controlled via the foot [2], and that the foot can control a camera during simulated laparoscopic surgery [8]. Wentzel et al. also used a foot-controlled robot to help with soldering [5]. Dougherty showed that subjects could control a robot with their foot to position a camera while navigating a maze with their hands [7]. In these examples, the robot was not attached to the person but performed the function of an additional limb. Additionally, the above research used some form of direct control to control the robot, likely because of the difficulty of getting an autonomous robot to understand and cooperate with a human user.

2.1. Foot Interfaces

In general, foot interfaces are a less explored method of control than hand interfaces. English et al. conducted some of the earliest work investigating foot/leg interfaces for human-computer interaction during the development of the modern computer mouse [12]. For new users, the leg performed similarly to the mouse, although the leg interface was more fatiguing and had a higher rate of errors. Since English's work, the hand mouse has become widely accepted. Pakkanen and Garcia conducted comparisons between hand and foot interfaces with position control [13, 14]. Garcia and Vu found that the performance on the foot interface increased significantly with practice [14]. When comparing foot and hand interfaces for modern work, the foot/leg interfaces may require more practice simply because of people's existing familiarity with the hand mouse. Several designs of foot interfaces have been designed and presented, all with a variety of input and sensor types [2, 7, 8, 12, 13, 17-20, 22, 24].

Velloso et al. organized a thorough survey of existing concepts of foot interfaces in which they are categorized into three types of sensing: mediated, intrinsic, and extrinsic [16]. Mediated sensing is sensing that occurs by physical interaction with an interface, intrinsic sensing makes use of sensors that are affixed to the leg and/or feet, and extrinsic sensing uses sensors that track the user's motions without physically interacting with the user. Mediated sensing can be seen in several everyday applications, such as a gas pedal in a car [16]. Intrinsic sensing examples are fitness trackers or modified shoes or insoles with sensors that track foot movements. Examples of extrinsic sensing are devices like a Microsoft Kinect or depth-finding camera.

English's work used mediated sensing in all the involved interfaces [12]. Later examples of mediated sensing can be seen in the work done by Pearson and Weiser. Pearson and Weiser proposed a series of foot interface designs, dubbed 'moles,' such as the foot swing or the pendulum mole [13], although the designs were never tested. Springer and Siebes designed and tested a foot interface that used both feet for control in lieu of a standard hand mouse [17]. The hand mouse was faster than the foot interface, and subjects stated that a one-foot interface would be preferable. Klamka et al. designed foot pedals that were used in conjunction with the hands to view and navigate maps [18]. Abdi et al. and Dougherty used mediated sensing to control SRLs that had attached cameras [7, 8].

Others have explored intrinsic sensing, often in the form of sensors attached to or embedded in shoes [19, 20]. Both Sasaki et al. and Resnick et al. have used intrinsic sensing to control SRLs [3, 21].

Extrinsic sensing has also been explored. A Microsoft Kinect was used by both Wentzel et al. and Abdi et al. to track foot movements [2]. Gunawardena and Hirakawa employed break beam sensors to identify foot gestures [22]. Sasaki's SRL sensors included extrinsic sensors to track the motion of the user's feet [3].

Interfaces that use mediated sensing are typically more intuitive for the user because the user gets some measure of feedback of the interface's position. Mediated sensing is also safer for robot control, since it is easier to disengage from a physical interface, thus decreasing unwanted input changes. For these reasons, mediated sensing will be used by the interfaces presented in this thesis. In addition to the type of interface, the type of control can also affect performance.

It is not entirely clear what control method makes for a good foot interface. With hand interfaces, position control typically performs better than rate control [23]. However, rate control is good when the workspace is large, or the robot's dynamics are slow [23]. Zhai and Milgram conducted a comparison of isotonic and isometric interfaces for both rate and position control for the hand [6], but there is much less research regarding the same factors for the foot. With a two-pedal setup, Kim and Kaber found that rate control was easier when using a foot interface [24]. Abdi et al. compared position and rate control for both isotonic and isometric interfaces, but they used only qualitative metrics and a small test group [25]. A planar foot interface was designed and tested by Dougherty to compare position and rate control [7]. Position control performed better at the primary tasks, but rate control had smoother trajectories and better stopping behavior, which is why the addition of friction to a foot interface is examined in this thesis. Determining the most intuitive and best performing combination of foot interface and control method would make controlling a robot significantly easier.

2.2. Controlling a Robotic Arm with a Foot Interface

Past research has tried to examine whether or not people can reliably use a foot interface to control a third arm. It has been shown that subjects can control virtual arms with their feet, or control a camera during surgery [2, 8]. Dougherty conducted an experiment with an SRL in which participants moved a marble through a maze with their hands while controlling a third arm that had an attached camera with their foot [7]. The shortcoming of Abdi's work is that the three-handed task was trivial to complete, and there were no metrics for performance. One of the issues with Dougherty's experiment was that the marble could move much faster than the robot, so subjects rarely moved the robot and their hand simultaneously. The task was too difficult due to factors unrelated to the coordination of three limbs, while Abdi's task was too easy. This thesis evaluates how well people can use their foot to control a robotic arm to perform a three-handed task that requires coordination of all three limbs to more clearly answer the question of how well people can coordinate with a robotic third arm. The task had to be difficult enough so that subjects would need three hands to complete it but easy enough so that differences in results would still be both measurable and comparable.

3. FIRST EXPERIMENT: FRICTION VS. NO FRICTION

In this section, friction was added to a foot interface so that it was easier for the user to stop and maintain a held position, and so that the user could remove their foot, thus removing the input, without affecting the input to the interface. A foot interface was developed that could have friction easily applied or removed. To compare the friction and no friction performance, a reaching task and a path-following task were used to evaluate how quickly users could reach targets and how accurately they can follow a path. The interface was compared with and without friction using the reaching and path-following tasks. Conventional wisdom is to remove friction from user interfaces, but no past research has investigated the effects of friction on a foot interface. This experiment shows that, in some cases, adding friction can benefit user performance.

3.1. Foot Interface

The interface created for this experiment uses two degrees of freedom, which only required rotation of the ankle, specifically dorsiflexion-plantarflexion and abduction-adduction. The design is a pedal, similar to the 4DOF device from Abdi but without the planar motion [8]. The maximum range of motion for the interface is 45° in dorsiflexion-plantarflexion, which is slightly less than most people's maximum range of motion, but is close to their maximum comfortable range of motion [16]. The planar rotation has a potential range of motion of 360°, but it was calibrated to each subjects' comfortable range for abduction-adduction, which was typically 30° to either side of the neutral position. The foot interface is shown in Figure 1.

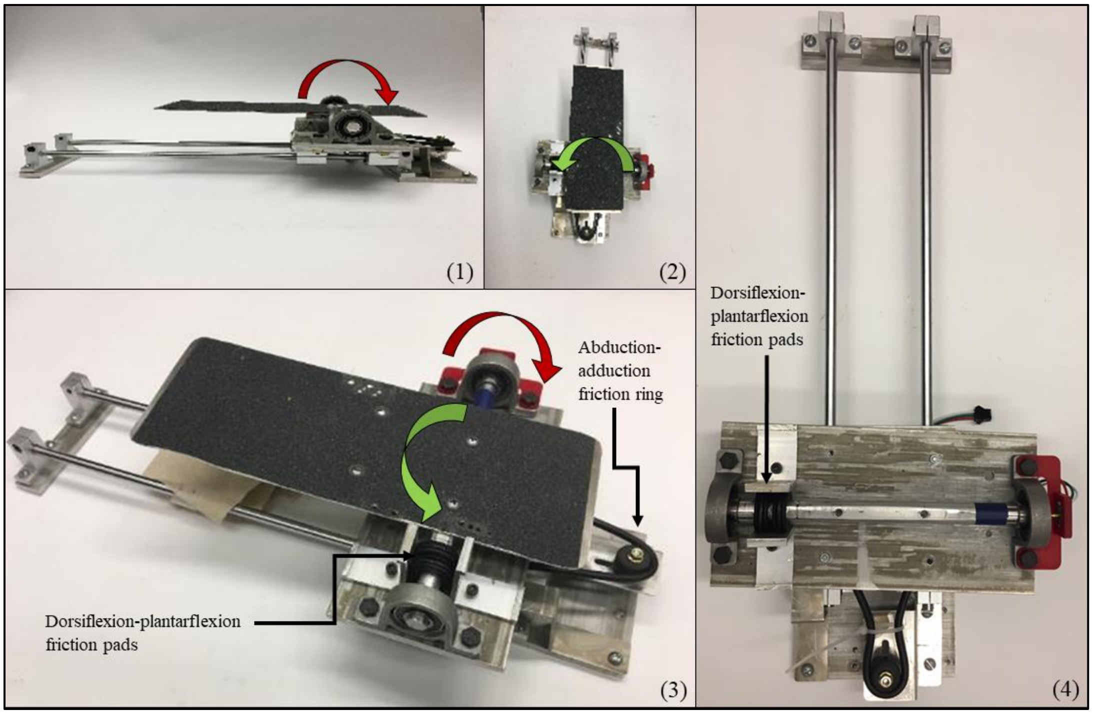

Figure 1. The foot interface allows for ankle rotation in the dorsiflexion-plantarflexion directions (dark red arrows), and abduction-adduction directions (light green arrows). The user's foot rests on the black pedal. The friction components can be quickly engaged or disengaged to switch between the friction and no friction interface. Images (2) and (4) are the same view, but with the pedal removed in (4).

To use the interface the user places their foot on the pedal with their ankle positioned above the center of rotation. This position both supports the weight of the leg and minimizes movement at the knee. Keeping practically all movement isolated to the ankle reduces the physical effort of the user.

Rotary potentiometers were used for sensing. An Arduino retrieved the sensor data, converted it to a joystick reading, and then passed the reading to the computer. After the Arduino received the sensor signals, a moving average filter was applied to smooth the output of the potentiometers. The moving average filter window was 30 readings.

Bearings were used in each DOF to minimize friction. With low friction, similar to previous devices, it was difficult and fatiguing to stop and hold a steady position. To address this issue, friction was added to the design. Friction was added for dorsiflexion-plantarflexion by attaching rubber pads to the axle. The rubber pads were compressed to reach the necessary amount of friction. Friction was added for abduction-adduction by looping an o-ring around the bearing. The o-ring was tensioned until the desired amount of friction was reached. The o-ring did not rotate with the bearing; the bearing rubbed against the o-ring, which caused the friction. Figure 2 shows how friction was applied to the interface. The level of friction had to be adjusted so that there was minimal static friction in either DOF, but enough so that the interface could maintain its position without the user acting on it. This ensured that the user could easily make fine input adjustments. The necessary amount of friction is highly dependent on the construction of the device, so for any given interface with friction, it must be adjusted manually until the right amount of friction is achieved. The added friction could be engaged and disengaged, so the same interface could be used with both friction and no friction in the experiment.

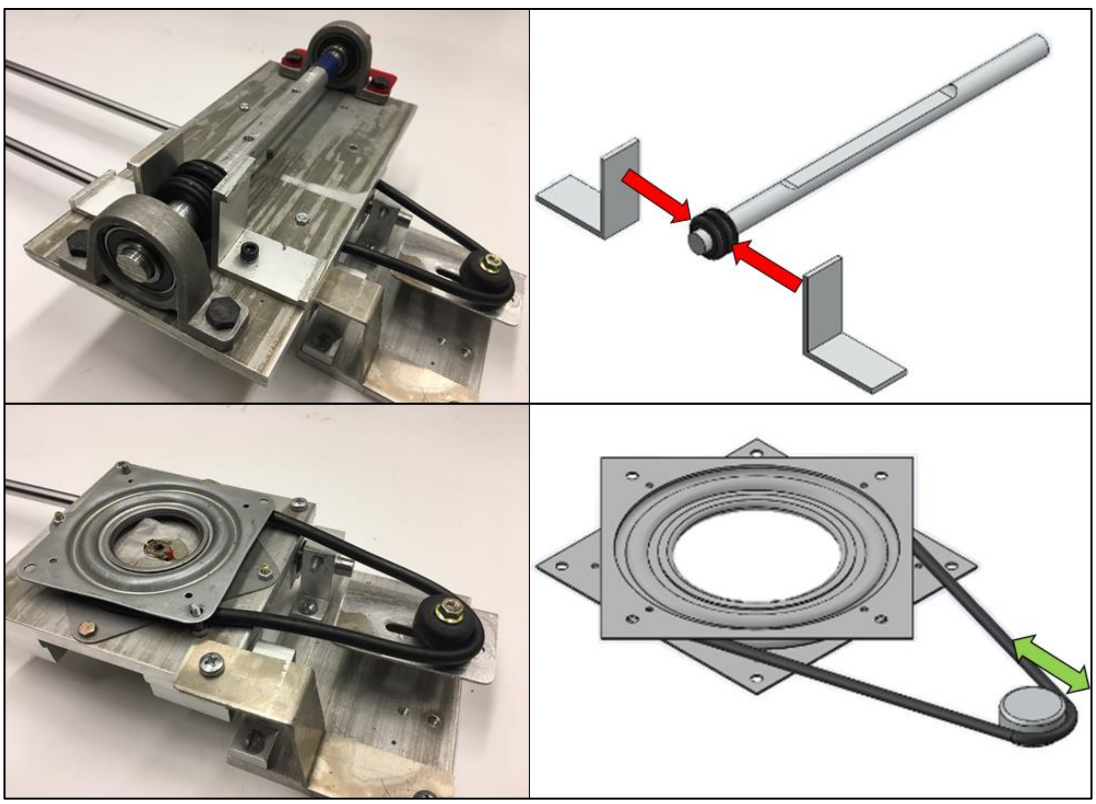

Figure 2. Pictured on the left are the parts of the interface responsible for rotation. Pictured on the right are visual examples of how the friction is adjusted for each degree of freedom. The friction in the dorsiflexion-plantarflexion directions is applied by compressing rubber pads on the pedal axle. It is adjusted by changing how much the L-brackets compress the pads, which is shown by the dark red arrows. The friction in the abduction-adduction directions is adjusted by applying tension to an o-ring that is looped around a bearing. The tension is adjusted by moving the tensioning disk in the direction of the light green arrow.

When the friction was disengaged the joints on the interface were completely free to rotate. While this allowed for easy movement in either direction, if the user wanted to maintain a position, they had to manually hold their foot in place. Engaging the friction in both degrees of freedom introduced a small amount of resistance during movement and made it easier to maintain a position, even allowing the user to remove their foot if they had to leave the interface, which was one of the goals of adding friction.

3.2. Experiment

The purpose of this experiment was to compare the performance of a position control foot interface with and without friction. Subjects completed two different kinds of tasks, reaching and path-following. Reaching was a time-critical task, and path-following was an accuracy-critical task. Having both types of tasks provided a more thorough evaluation of subject performance. Subjects were evaluated based on how quickly they could reach a target, how well they could hold a position, and how well they could make slow, accurate movements. Each task was completed using the foot interface both with and without friction.

There were two target sets, A and B, for each task. Two target sets were used, so test subjects did not repeat the same set for both friction and no friction versions of the tasks. This prevented subjects from learning the sequence of targets and paths presented to them. Sets A and B in the reaching task had points that were equally distributed between short, medium, and long distances, and in the path-following task, the total distance traveled for both sets was equal. There were no significant performance differences between subjects that completed different target/path sets. Participants were organized into four groups so that subjects were equally distributed between the orders of the interfaces and target sets used. Table 1 shows the group distribution. Every subject completed all four tasks, which covered reaching and path-following with and without friction.

Table 1: Participants used both interfaces and target/path sets according to the order shown. The first letter indicates the interface, with F for friction and N for No Friction. The second letter indicates the task, with R for reaching and P for path-following. The third letter indicates the target/path set, either A or B. Tasks are listed in order from left to right for each group.

Group 1	FRA	FPA	NRB	NPB
Group 2	NRB	NPB	FRA	FPA
Group 3	FRB	FPB	NRA	NPA
Group 4	NRA	NPA	FRB	FPB

Each subject was given two minutes of practice time before each task so they could familiarize themselves with the task and interface. Subjects were allowed to ask questions during the practice time but not during recorded sessions. All tasks began with a five-second period in which subjects would ensure they were centered on screen. After the five-second centering period, the task would begin. Upon completion of each task, the participants filled out a modified NASA Task Load Index (TLX), which rated the mental, physical, and temporal demands, as well as the level of perceived performance, effort, and frustration. The NASA TLX is listed in Appendix A.

For the reaching task, shown in Figure 3, participants were instructed to move a red cursor into a yellow, circular target as quickly as possible without worrying about the path taken to reach the target. The target was considered reached after the cursor remained in the target for one second. The one second holding time prevented subjects from simply passing through the target to complete the task. After the one second holding time, a white circle would appear as a preview of the next target location so the subject would have a moment to see and plan their motion towards their next target. A random delay between 0.5 and 1.5 seconds was set before the target position would switch to the preview so that subjects could not anticipate the switch.

Figure 3. In the reaching task the user must move their cursor between a series of targets as quickly as possible. The user's cursor is red while not inside the target, the yellow circle (a). The cursor turns green when inside the target, and a white dot provides a preview of the next target location after the cursor has been inside the target for one second (b).

The path-following task, shown in Figure 4, was similar to the reaching task in that the subjects needed to move to a target point and hold the position for one second, but there was the added element of following a specified path. Participants were instructed to follow the displayed path as accurately as possible, and not to worry about the time taken to complete the task. The preview and delay characteristics of the reaching task were identical in the path-following task, with the added preview of the path to be followed. Path types cycled between straight lines, straight corners, quadratic curves, and cubic curves. An example of each path type is shown in Appendix B.

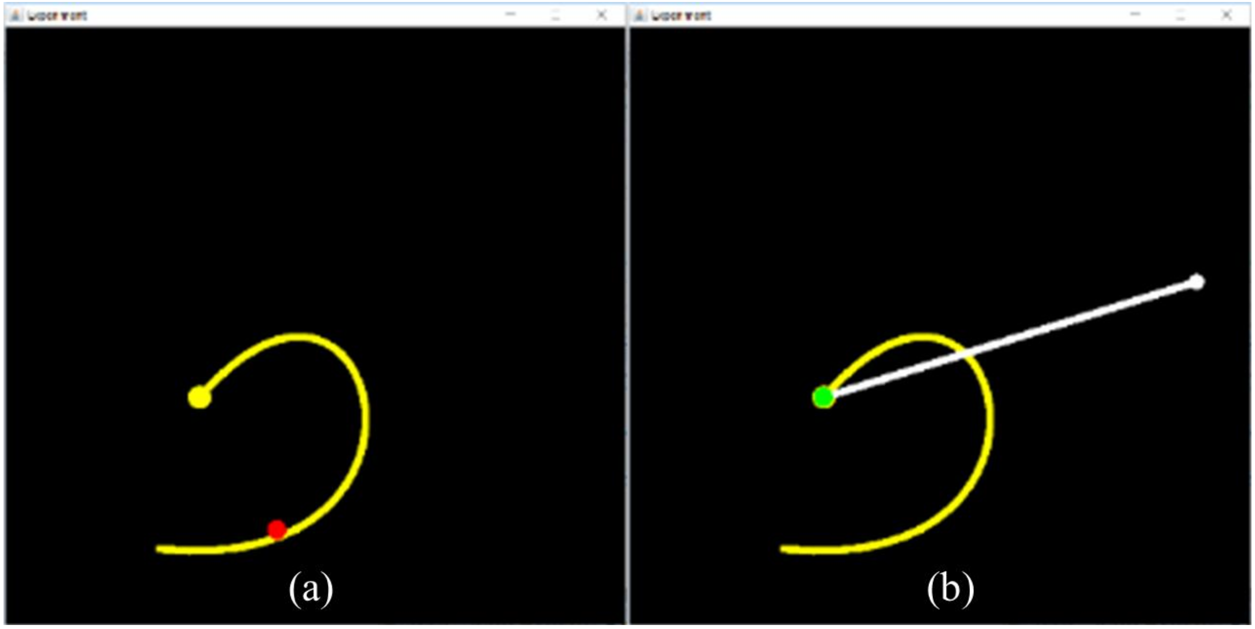

Figure 4. In the path-following task the user must move their cursor along a series of specified paths. The user's cursor is red while not at the endpoint of the yellow path,(a). The cursor turns green when at the target, and a white preview of the next path is displayed after the cursor has been in the target for one second (b).

Twenty participants were recruited for this experiment. Participants were asked for demographic information including, age, dominant foot, gender, and weekly time spent playing videogames. Of the 20 participants, 15 were male, and 5 were female. The average age of all participants was 27.95. 18 subjects were right foot dominant, and 2 were left foot dominant. Subjects always used their dominant foot on the interface. The average amount of weekly videogame hours was 5.3. To check for significant differences between demographic groups, the data was separated into the relevant groups and compared. No noticeable performance differences were noted from demographic variations.

3.3. Analysis

The reaching task performance was evaluated using four metrics: completion time, distance ratio, settling time, and settling distance. The completion time was the sum of both the travel time and settling time of each individual path. The travel time started with each new appearance of a target and ends as soon as the target zone is reached. Settling time was defined as the time from when the cursor first enters the target to when it remains in the target for one second. The distance ratio was found by taking the distance traveled between targets, from when the subject first started moving to when they first entered the target, then dividing it by the shortest straight-line path between targets. A perfect trajectory has a distance ratio of one. The settling distance was defined as the distance traveled from when the cursor first entered the target to when it remained in the target for one second. If a subject left the target zone, then the settling time and distance continued to increase. Once the subject re-entered the target the one-second timer reset.

There is no firmly established metric to evaluate path-following performance, so several measurements are reported here. First, the subjects' trajectory data was interpolated so that there was the same number of data points for every path. Without the interpolation, slower trajectories would have had more points, which means more distances would have been added in the $\mathcal{L}_2$-norm calculation. In other words, even if two subjects performed the same on a path, the slower one would have a higher $\mathcal{L}_2$-norm.

The distance from the desired path was recorded from the nearest point on the desired path to the subject's current position, as can be seen in Figure 5. However, the point on the desired path to which the subject's position was compared was monotonically increasing, meaning if a subject moved backward, the corresponding point on the desired path would not move backward, but would instead stay the same. Therefore, backtracking was penalized as though the cursor was moving farther away from the desired path. For example, say d_n is the distance between the point on the recorded trajectory and a given point on the desired path, and d_{n+1} is the distance from the trajectory point to the next point on the desired path. The index n can only increase in value or stay constant. If $d_n < d_{n+1}$, then d_n will be the recorded value, even if $d_{n-1} < d_n$. Figure 6 shows an example of the monotonically increasing points on the desired path.

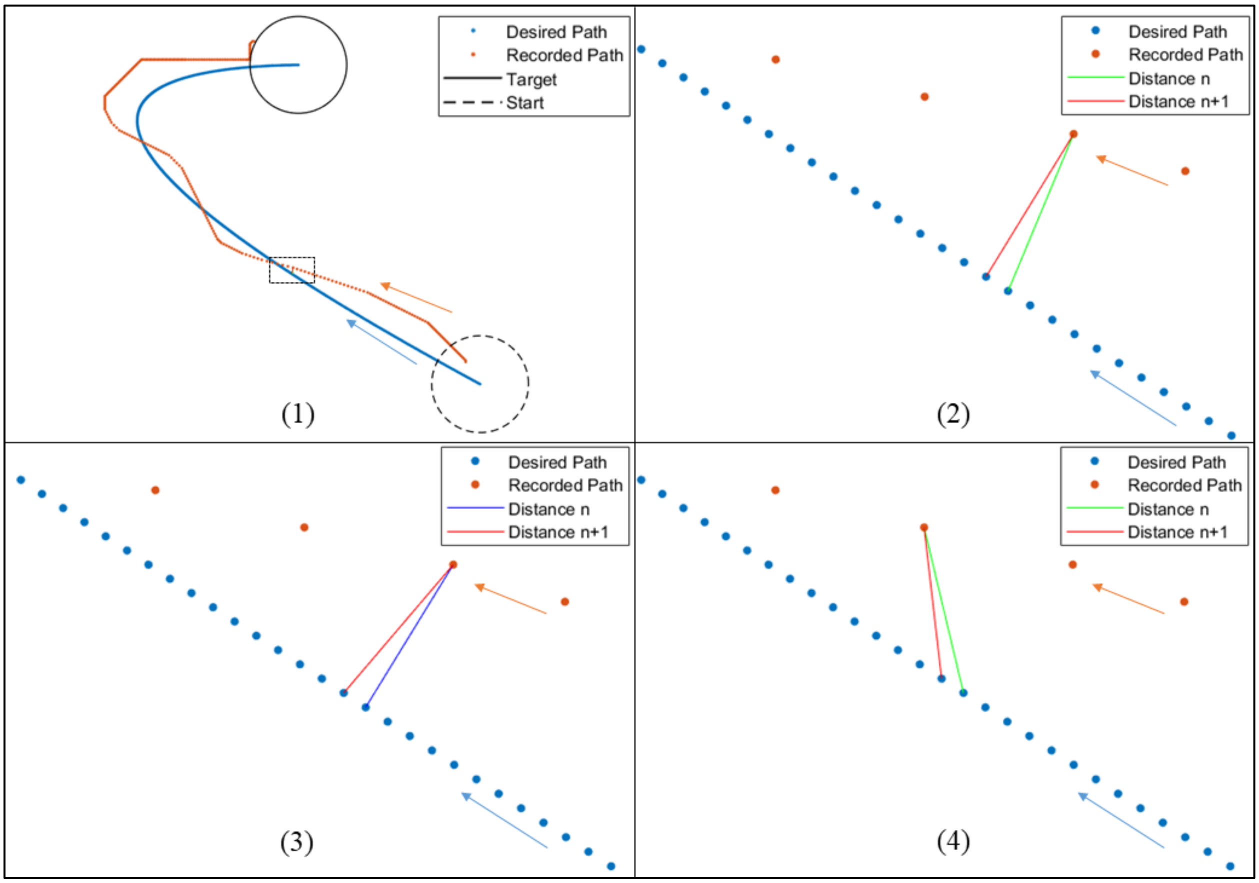

Figure 5. An example of the path-following evaluation. The blue arrow shows the desired direction. The orange arrow shows the direction of the trajectory. (1) The trajectory that is being evaluated. (2) The distance from two points on the desired path to a point on the recorded trajectory are being compared. The distance to the current point (green) is longer than the distance to the next point (red). (3) The distances to the current point (blue) is now less than the distance to the next point, meaning the shortest distance between the desired path and the given point on the recorded trajectory has been found, and thus will be recorded. (4) The process repeats for the next point on the recorded trajectory. When trying to find the shortest distance, the first tested point on the desired path was the last point used in the previous distance evaluation.

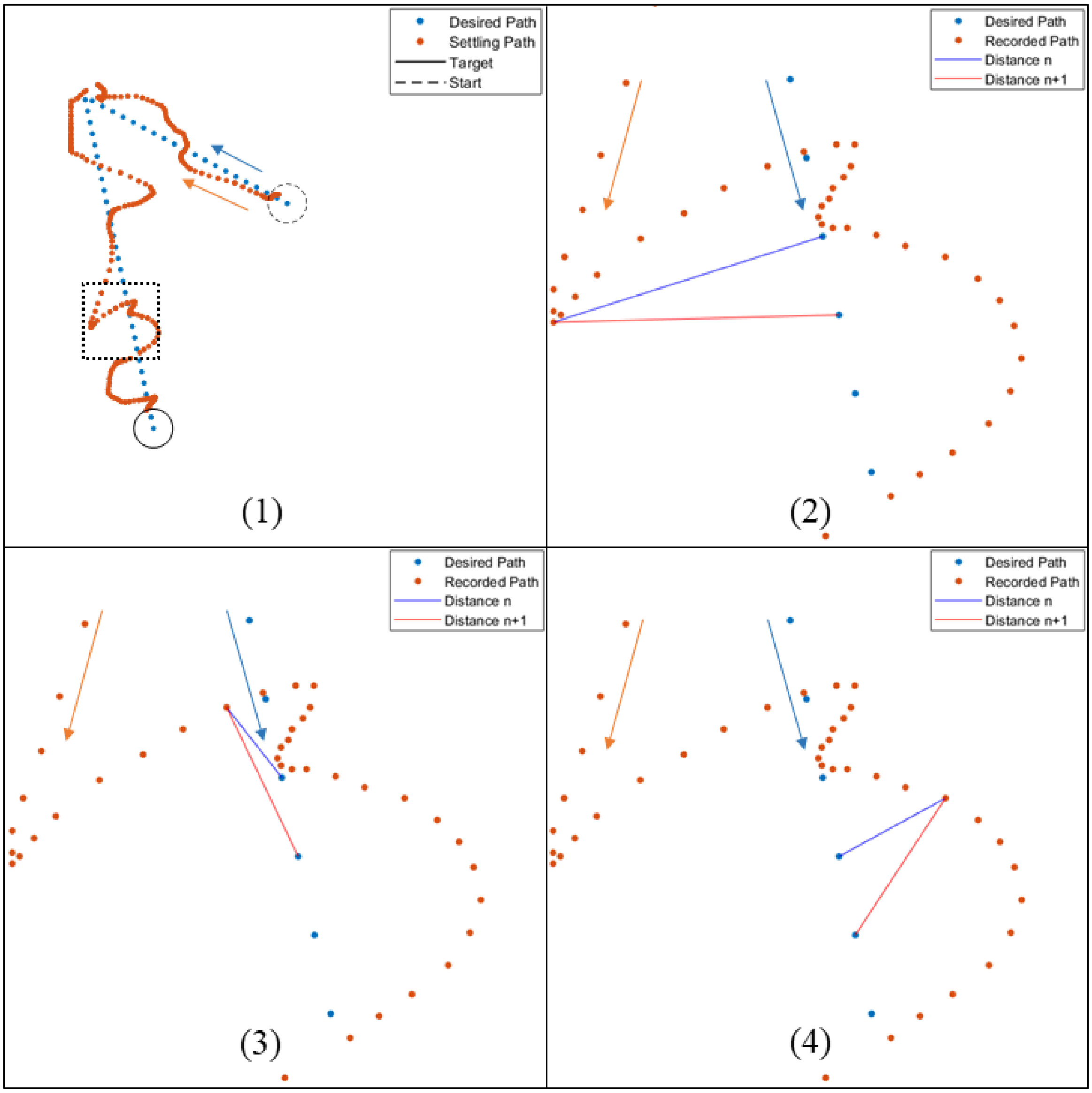

Figure 6. An example of the monotonically increasing points on the desired path. The blue arrow shows the desired direction, and the orange arrow shows the direction of the trajectory. (1) The trajectory that is being evaluated (2) The distance is recorded as usual, with the closest points on the desired path and recorded trajectory. (3) The trajectory is backtracking. Although the point from the trajectory is closer to a different point on the desired path, the desired path index has already moved forward, so the trajectory point is compared to the last point on the desired path that was used. (4) The trajectory is moving forward again, so the point on the desired path also moves forward.

After the data processing, every subject had a vector of distances between their path and the desired path. From this vector of distances, the infinity norm, mean distance, and $\mathcal{L}_2$-norm were each computed. The infinity norm was used as a measure of the worst-case error during a given path. Both the mean distance and the $\mathcal{L}_2$-norm were used as measures of how well the path was followed for the full length of the path. The $\mathcal{L}_2$-norm was the square root of the sum of the squares (i.e., the Euclidean length) of the vector of distances from the desired path. This $\mathcal{L}_2$-norm was then normalized by the path length so that longer paths could be treated the same as shorter paths. Following the path perfectly would result in a $\mathcal{L}_2$-norm of zero. If a subject were to perfectly follow a path, except for a single large deviation, the $\mathcal{L}_2$-norm and mean would simply show a low value, whereas the infinity norm would be the largest magnitude of deviation.

3.4. Results and Discussion

A. Reaching

Sample trajectory data for the reaching task is shown in Figure 7. The measured path can start from anywhere within the previous target zone, which is why it does not share the start point with the shortest possible path.

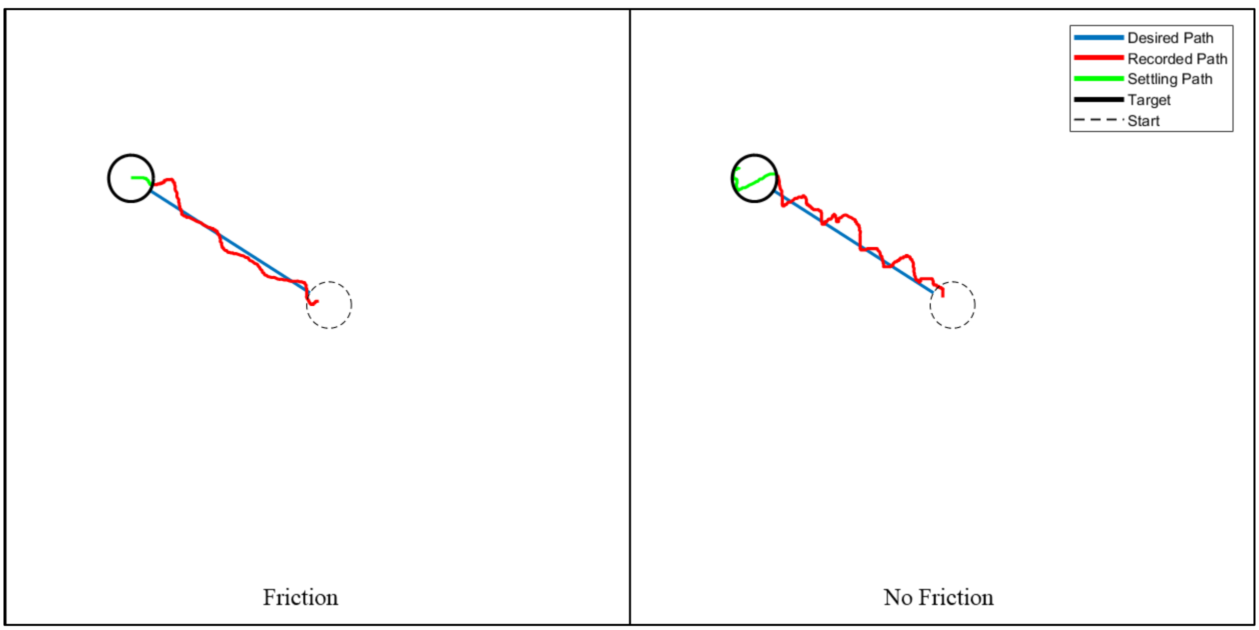

Figure 7. This raw trajectory data gathered from the reaching task shows both friction and no friction trajectories for the same target. The red line indicates the path traveled by the subject to the target, and the green line indicates the path traveled after entering the target, shown in black. The previous target is the dashed black line. The blue line shows the shortest possible travel path.

A paired t-test was used to evaluate the differences in performance for the reaching task. The paired t-test accounted for subject dependence. Visual inspection of the settling time data reveals that it was not normally distributed. Because of the non-normal distribution of the settling time data, the Wilcoxon signed-rank test was used to compare the settling time. The alternative hypothesis for each metric was that the difference between the paired observations of friction and no friction were less than zero, with the null hypothesis of the difference being equal to zero. The p-values from the paired t-tests and Wilcoxon signed-rank test are shown in Table 2. The α value was 0.05 for 95% confidence. Box plots for the measured metrics of the reaching task are shown in Figure 8. Additional box plots showing the difference in performance for both tasks are listed in Appendix C.

Table 2. P-values for the comparison between the friction and no friction interfaces in the reaching task. A value of less than 0.05 indicates a rejection of the null hypothesis in favor of the alternative hypothesis at 95% confidence. Significant values are shown in bold. For the reaching task there was a significant difference for the settling time and settling distance.

		P-value
Reaching	Completion Time	0.494
	Distance Ratio	0.589
	Settling Time	**0.021**
	Settling Distance	**0.040**

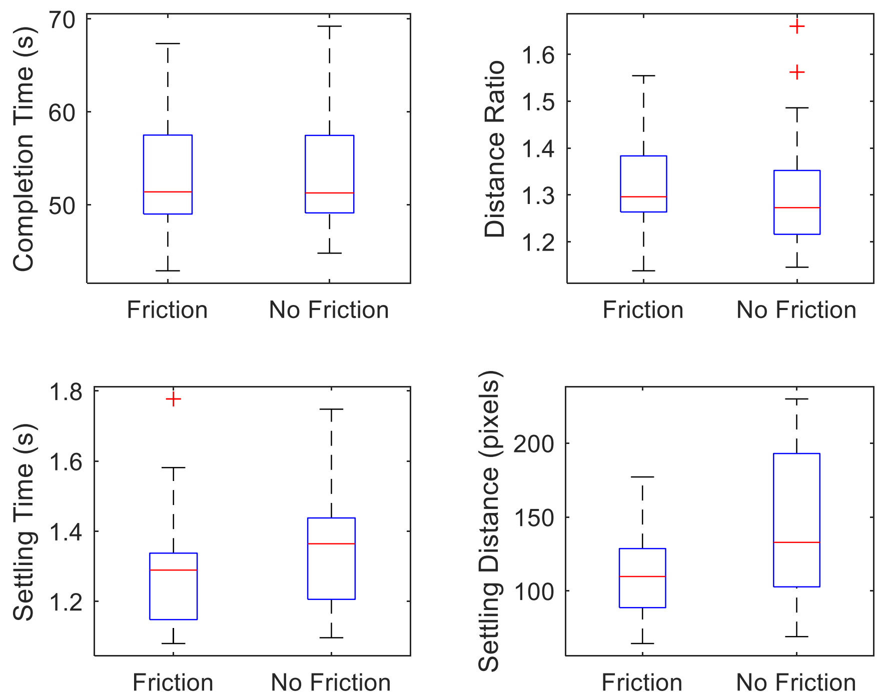

Figure 8. These box plots show the performance of the friction interface and no friction interface for the reaching task. The addition of friction reduced the settling time and distance.

The performance of each interface was very similar for this task, but there was a significant reduction in settling time and distance with the addition of friction. This shows that subjects were less likely to overshoot the target, moved less within the target once they arrived, and spent less time settling on the target. Friction helped subjects stop and hold a fixed position. This benefit did not come at the cost of increased completion time, as there is no significant difference between the completion times for either interface. Additional subject trajectories are shown in Appendix D.

B. Path-Following

Sample trajectory data from the path-following task are shown in Figure 9. The infinity norm measures the worst-case errors of subjects while the $\mathcal{L}_2$-norm and mean evaluate the path-following performance for the full trajectory of each path. The completion time was the total time required to complete the task. The mean and standard deviation of the metrics and survey results are listed in Appendix E.

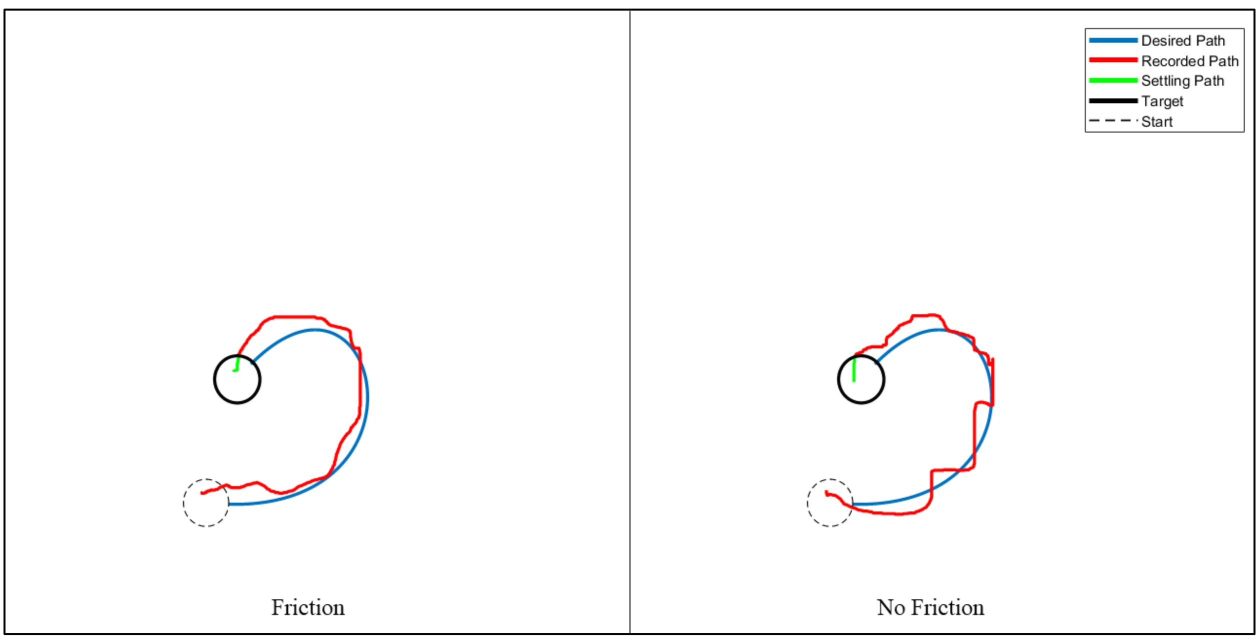

Figure 9. This raw trajectory data gathered from the path-following task shows both friction and no friction trajectories for the same path. The red line indicates the path traveled by the subject, and the green line indicates the path traveled after entering the target, which is shown in black. The starting zone is the dashed black circle. The blue line is the desired path.

A paired t-test was used to evaluate the differences in performance for the path-following task for the same reasons listed for the reaching task. The alternative hypothesis for each metric was that the difference between the paired observations of friction and no friction were less than zero, with the null hypothesis of the difference being equal to zero. The p-values from these paired t-tests are shown in Table 3. The α value was 0.05 for 95% confidence. Box plots for the path-following task are shown in Figure 10.

Table 3. P-values for the comparison between the friction and no friction interfaces for the path-following. A value of less than 0.05 indicates a significant difference at 95% confidence. There was no significant performance difference for the path-following task.

		P-value
Path-Following	Mean Distance	0.064
	Infinity Norm	0.164
	Standardized 2-Norm	0.061
	Completion Time	0.857

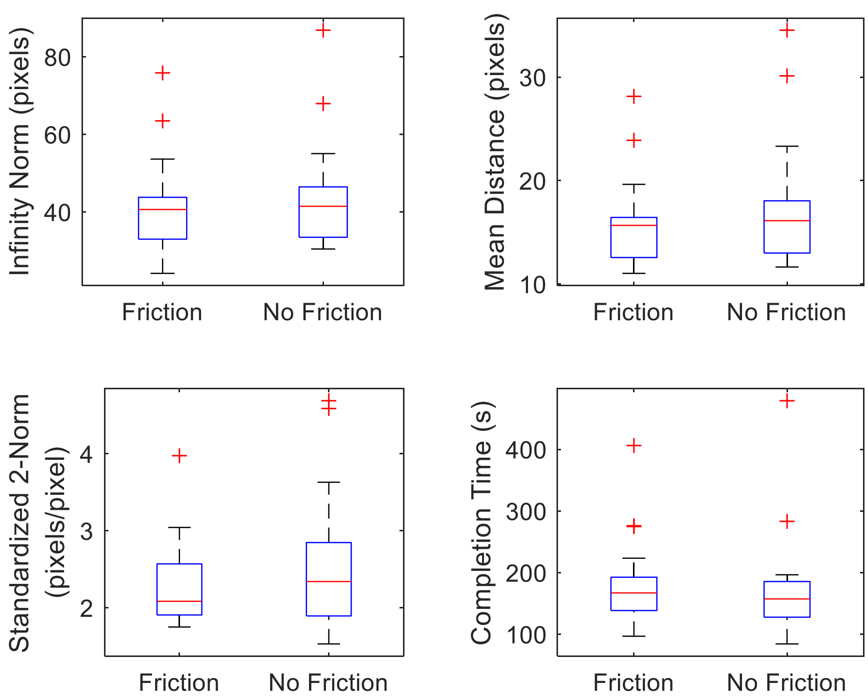

Figure 10. These box plots show the performance of the friction interface and no friction interface for the path-following task.

There was no significant difference between the two interfaces for the path-following task. This shows that adding friction to the interface does not have an adverse effect on performance for an accuracy-critical task.

Adding friction to the foot interface had little noticeable effect on performance, partly because the amount of resistance added was not large. However, the resistance was large enough to result in significant differences in the settling time and settling distance during the reaching task. The friction reduced overshoot and made it easier to hold position, thus reducing the distance needed to stop at the target. While there was no significant difference between the interfaces for the path-following task, most subjects indicated a preference for the friction device because it prevented them from unwanted, sudden jerky motions while navigating the path.

During testing, all subjects commented that they preferred the friction interface for path-following, but some subjects preferred the no friction interface for reaching. The average scores from the NASA TLX survey results, shown in Figure 11 and Figure 12, support the anecdotes of the test subjects, showing a perceived preference for the friction interface. It can be seen that the friction interface scored slightly better than the no friction interface, although both interfaces have similar scores.

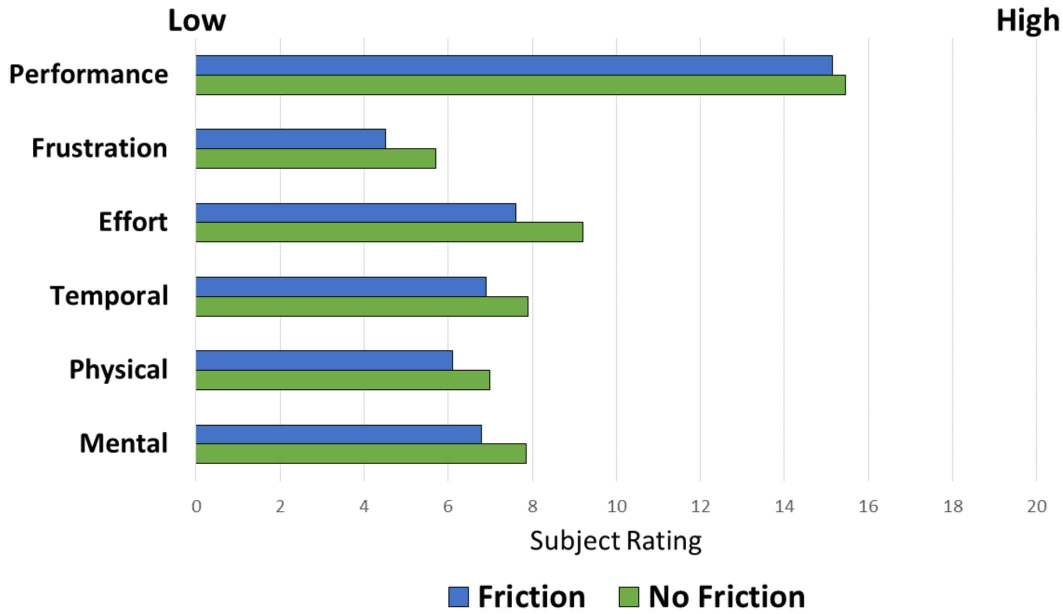

Figure 11. NASA Task Load Index values for both interfaces in the reaching task. Scores are rated with a low score of zero and a high score of twenty, with ten being neutral. A lower score is better for all metrics except performance.

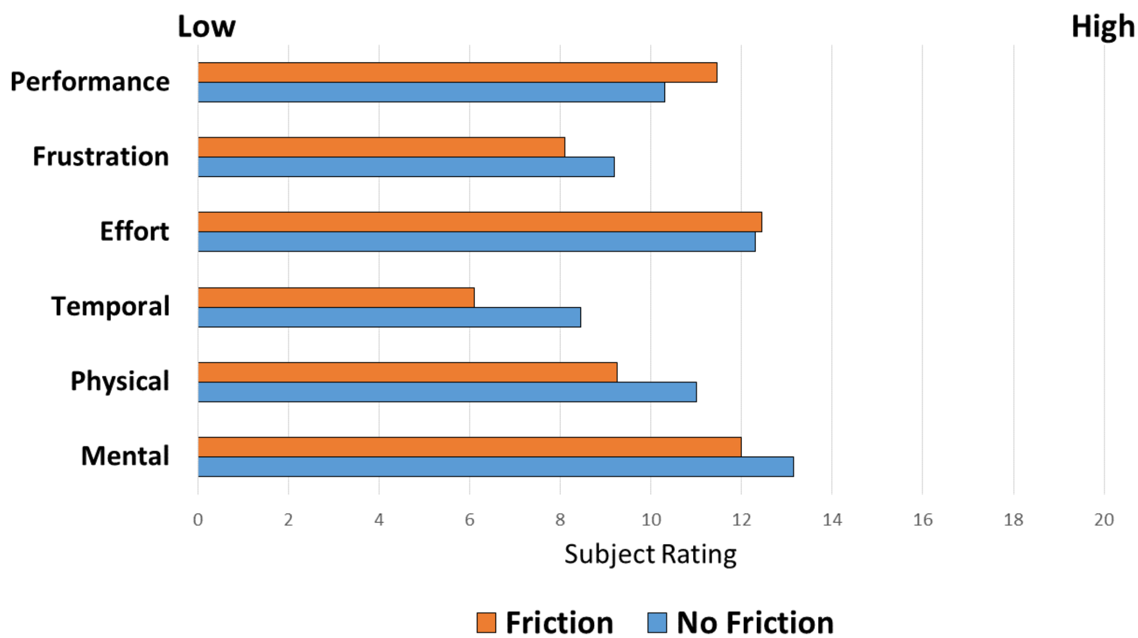

Figure 12. NASA Task Load Index values for both interfaces in the path-following task. Scores are rated with a low score of zero and a high score of twenty, with ten being neutral. A lower score is better for all metrics except performance.

3.5. Summary

The results from both interfaces showed that friction improved subjects' ability to stop and hold position while not negatively affecting their ability to move quickly or accurately.

Feedback from the test subjects indicated there was an overall preference for the friction interface. This outcome supports the conclusion that adding friction to a foot interface is beneficial, as it is more comfortable, easier to use, and allows the user to hold position with less effort. Friction also has the added benefit of maintaining a position without user input, so the user can step away from the interface. There was only a small difference in fatigue, which was based on effort and physical demand for either device, which may be due to the short duration of the tasks, which took between 2-5 minutes for each subject. Although this experiment features a foot interface, the relationship between friction and no friction can likely be applied to hand interfaces. Arms have less inertia than legs, but position control hand interfaces have some of the same challenges as described in this paper, such as holding a position with no effort. The other experiments discussed in this thesis will include friction for position control because it improves performance. In the next section, isometric foot interfaces will be investigated. Since an isometric interface would not need the foot to move at all, it may help further reduce fatigue.

4. SECOND EXPERIMENT: ISOMETRIC INTERFACE COMPARISON

Thus far, this thesis has only examined isotonic foot interfaces. Another type of input is isometric, which reads forces and/or torques as input, eliminating the need for movement from the user. By removing user motion and supporting the weight of the leg, an isometric interface may be less fatiguing. An isometric interface can also make use of larger leg muscles and has the added benefit of being easily adaptable to higher DOFs. The 2DOF isometric interfaces were evaluated with the same reaching and path-following tasks from the previous experiment. The isometric interface was also used to compare position and rate control. Unlike the isotonic interfaces, rate control performed better than position control, plus there was very little difference between isometric rate and isotonic rate control, although rate control performed marginally better.

4.1. Foot Interfaces

A. Isometric

The isometric interface, shown in Figure 13, consists of a 6DOF force/torque sensor that is fixed to the ground. The sensor is a Gamma US-15-50 from ATI Industrial Automation. A rectangular plate is attached to the top of the sensor. The plate allows the user to place their foot on the sensor. A series of straps were used to rigidly attach the user's foot to the plate so that any attempted rotation is immediately translated into a torque. Torque was used because, during development, it was found that it is easier and more comfortable to apply a torque instead of a force. This was an anecdotal observation rather than a user study. Only 2DOFs, torques about X and Z, as shown in Figure 13, are used for the interface.

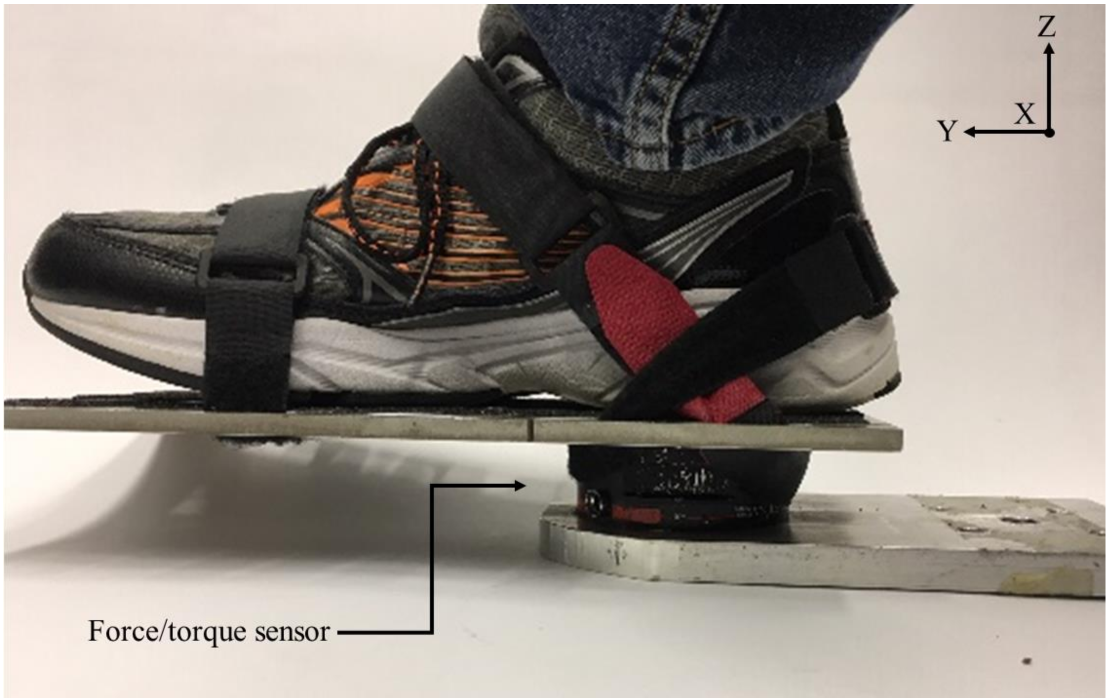

Figure 13. The isometric interface reads torque inputs in the dorsiflexion-plantarflexion directions and abduction-adduction directions. The user's foot is strapped to the sensor plate to keep their foot rigidly attached.

The maximum torque about the axes of rotation of the sensor is ±50 in-lbs, with a resolution of 1/160 lbf/in. The interface was calibrated to each user so that their maximum comfortable torque applied corresponded with the maximum/minimum position readings for the experiment. To do this the user was strapped onto the interface, and then they exerted the maximum torque they could comfortably apply, which was then set as the maximum output. The isometric interface was used for both position and rate control.

B. Isotonic

As with the isometric interface, an isotonic interface was used for both position control and rate control. The isotonic position interface was the same device described in Section 3.1.

The isotonic rate control interface is also a 2DOF pedal, shown in Figure 14, but features spring returns so the interface moves to the zero position when no input is applied. There is also a strap that goes around the user's foot to keep the front of the foot engaged with the pedal. The maximum range of motion was 40° in dorsiflexion/plantarflexion, and 35° to either side of the neutral position in abduction/adduction.

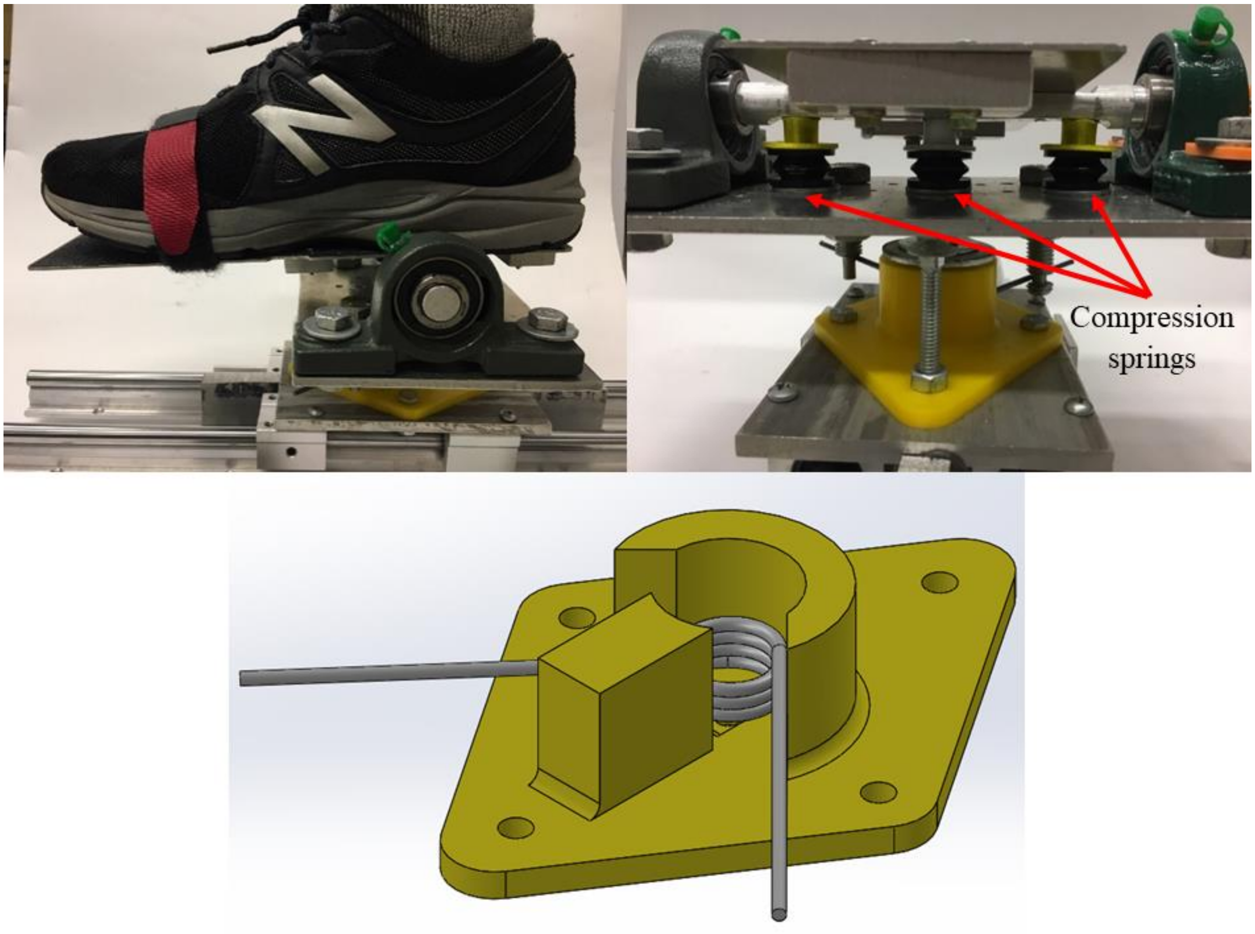

Figure 14. The isotonic rate control interface allows for ankle rotation in the dorsiflexion-plantarflexion directions (red arrow), and abduction-adduction directions (green arrow). The user's foot rests on the black pedal. When the user relaxes or removes their foot the device returns to the neutral position via spring return. The Y-axis spring return is achieved with a series of compression springs, and the X-axis spring return is achieved with a torsion spring.

The spring return for the dorsiflexion-plantarflexion DOF was achieved by attaching three parallel compression springs to the axis of rotation. The design mimicked the spring return of a typical hand joystick so that the same 'spring back' response was achieved. Three shorter springs were used due to spatial constraints. The total spring stiffness of the springs was approximately 60 kN/m. This is a very high spring constant, but the displacement and the lever arm for applying the force was very small (less than 0.5 in). This spring configuration was designed by Morris [26].

The spring return in the abduction-adduction DOF was accomplished by using a torsion spring. This design also mimicked the design of a hand joystick. Rotating the foot to either side would compress the spring, causing the interface to snap back to center when the user relaxed their foot. The spring stiffness of the torsion spring was approximately 2.5 N-m. While this spring constant is much smaller, the lever arm on the torsion spring was significantly longer than the one for the compression springs, and it is much easier for people to push down and pull up with their foot than it is to twist left and right, so the torsion spring did not need to be as strong as the compression springs.

To use the isotonic interfaces, the user placed their foot on the pedal with their ankle positioned above the center of rotation. This position both supports the weight of the leg and requires no movement of the leg, which reduces user fatigue.

An Arduino was used to process the sensor data and convert it into a joystick signal. Like in the first experiment, in Section 3.2, a moving average filter was used to smooth sensor outputs after they were sent to the Arduino. The moving average filter window was 30 readings.

4.2. Experiment

The purpose of this experiment was to compare the performance of isometric foot interfaces for rate and position control and to see how the relationship between the isometric interfaces compared to that of the isotonic interfaces. Subjects completed two different kinds of tasks, reaching and path-following, for the same reasons as listed in the previous experiment. Each task was completed with all combinations of interface and control method.

During initial testing it was found that there was a statistically significant improvement in performance when subjects returned and repeated the experiment after a minimum of 24 hours, suggesting that the added experience with the interfaces improved performance. For the recorded experiment, each subject participated in two sessions.

There were two target sets, A and B, for each task. Sets A and B in the reaching task had equally distributed targets, and in the path-following task, both sets had equal total distances. The A and B sets were alternated, so test subjects did not repeat identical paths with a given interface type in a single session. This was to minimize learning effects. The order was flipped for the second session, so the same set and interface were never repeated twice. Participants were organized into four groups so that subjects were equally distributed between the orders of interface, control method, and target/path sets used. Table 4 shows the group distribution. Every subject completed both tasks with isotonic position (ITP), isotonic rate (ITR), isometric position (IMP), and isometric rate (IMR).

Table 4. Participants used every interface in the order shown for each session. ITP is isotonic position, ITR is isotonic rate, IMP is isometric position, and IMR is isometric rate. Blue indicates target set A, and green indicates target set B. Shown below is the ordering for session 1. The ordering for session 2 was distributed the same, but the order of the target set was inverted.

Subject Grouping	Interface and Target Set			
Group 1	ITP	ITR	IMP	IMR
Group 2	IMP	IMR	ITP	ITR
Group 3	ITR	ITP	IMR	IMP
Group 4	IMR	IMP	ITR	ITP

Each subject was given two minutes of practice time before each task so they could familiarize themselves with the task and interface. Questions were allowed during practice but not during recorded sessions. All tasks began with a five-second period in which subjects would center their cursor on the screen. After the centering period, the task would begin. Upon completion of each task, the participants filled out a modified NASA Task Load Index (TLX), which rated the mental, physical, and temporal demands, as well as the level of perceived performance, effort, and frustration. Subjects also filled out a survey to indicate which interface they preferred. The preference survey is listed in Appendix F.

The reaching and path-following tasks described here are identical to those described in Section 3.2, except for each interface, there are only twelve targets/paths. This reduction of the target sets was to limit how long the experiment took for each subject.

For the reaching task, shown in Figure 15, participants were instructed to move a red cursor into a yellow, circular target as quickly as possible, and that the path traveled while reaching the target was unimportant. Once the cursor stayed in the target for one second, the target was recorded as reached. The one second holding time tested subjects' ability to hold the cursor steady, and it penalized overshooting the target because subjects could not simply pass through the target to complete the task. A preview of the next target position, displayed as a solid white circle, appeared after the one second period. This preview gave the subject a moment to see and plan their motion towards their next target. A random delay between 0.5 and 1.5 seconds was set before the target position would switch to the preview so that subjects could not anticipate the switch.

Figure 15. In the reaching task the cursor must be moved between a series of targets as quickly as possible. The cursor is red while not inside the target, the yellow circle (a). The cursor turns green when inside the target, and a white dot provides a preview of the next target location after the cursor has been inside the target for one second (b).

The path-following task, shown in Figure 16, required subjects to follow a path to reach the target. Participants were instructed to follow the displayed path as accurately as possible, and that time taken to do so was unimportant. The preview and delay characteristics of the reaching task were identical in the path-following task, with the added preview of the path to be followed. Path types cycled between straight lines, straight corners, quadratic curves, and cubic curves.

Participants were asked for demographic information: age, dominant foot, and gender. The subjects in this experiment were different subjects from those in the first experiment. Twenty participants were recruited for this study: 17 male, 3 female. The average age of participants was 22.4 years. 19 subjects were right-foot dominant, 1 was left-foot dominant. Subjects used their dominant foot during the experiment. Like in the first experiment, differences between demographic groups were examined by separating the data into the relevant groups and comparing the results. No noticeable performance differences were noted from demographic variations.

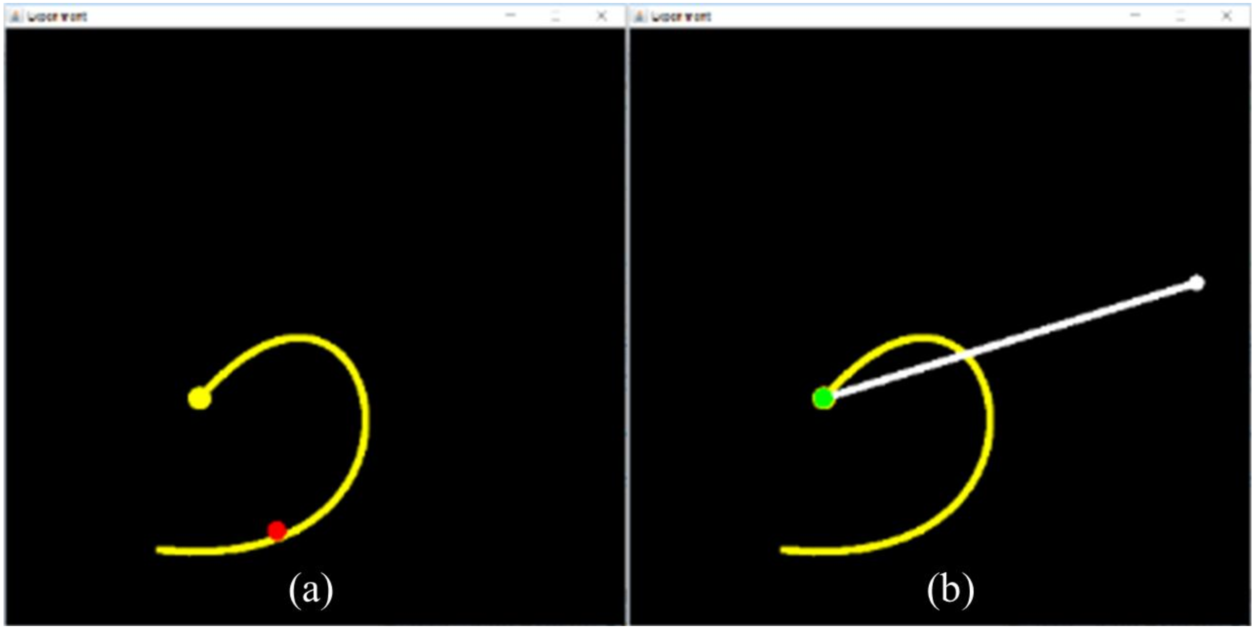

Figure 16. In the path-following task the user must move their cursor along a series of specified paths. The user's cursor is red while not at the endpoint of the path, displayed in yellow (a). The cursor turns green when at the target, and a white preview of the next path is displayed after the cursor has been inside the target for one second (b).

4.3. Analysis

The reaching and path-following tasks were evaluated with the same metrics and evaluation method, as was explained in Section 3.3. Both session 1 and 2 were analyzed. Session 1 produced the same relationships and conclusions as session 2, and session 2 showed noticeable improvement in performance from the added practice, so session 2 will be shown and discussed in this chapter. The results and from session 1 are listed in Appendix G.

4.4. Results and Discussion

A. Reaching

Sample trajectories for each interface are shown in Figure 17. The recorded path data can start from anywhere within the previous target, so it does not necessarily share the start point with the shortest possible path. Additional subject trajectories are shown in Appendix D.

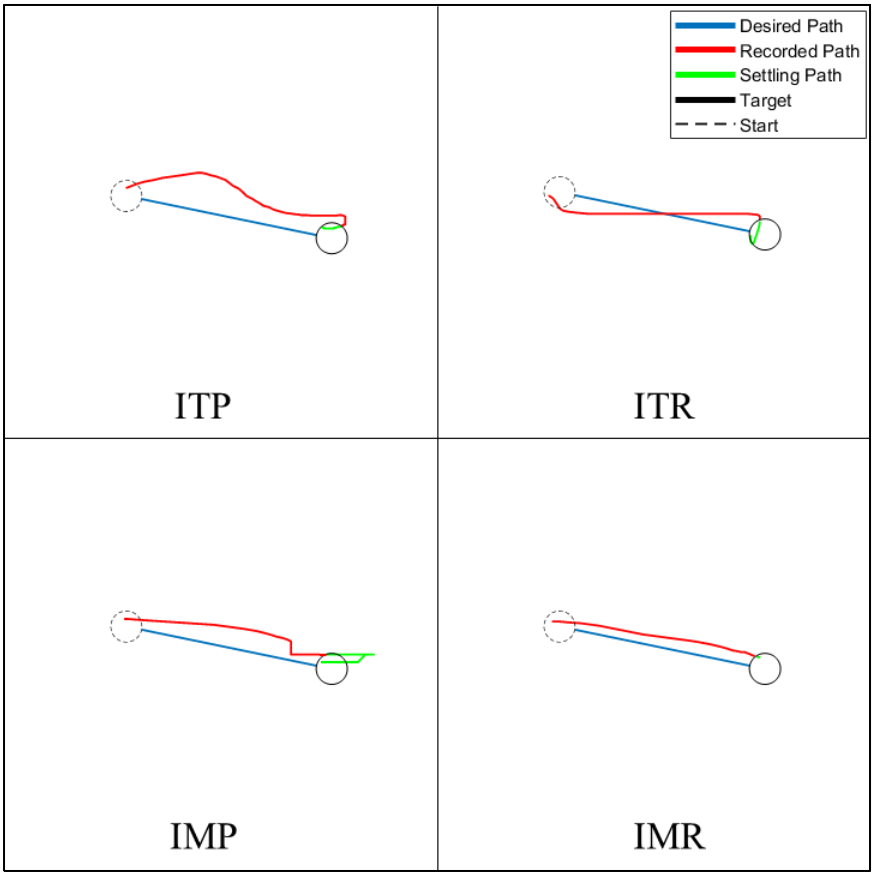

Figure 17. This raw trajectory data gathered from the reaching task shows examples of trajectories from each interface for the same target The red line is the path traveled by the subject to the target, and the green line is the path traveled after entering the target, shown in black. The previous target is the dashed black line. The blue line is the optimal trajectory.

A multiple comparison ANOVA analysis was used to compare the performance of the interfaces for the reaching task. P-values of the analysis are shown in Table 5. The Bonferroni correction was used to compensate for multiple comparisons, so the α value for 95% confidence was 0.0083. The ANOVA analysis accounts for subject dependence by evaluating subjects relative to their own performance, so if one subject performs better than another, then the analysis results are not affected. Box plots of the analyzed data are shown in Figure 18.

Table 5. P-values for the comparison between the interfaces for the reaching task. A value of less than 0.0083 indicates a significant difference at 95% confidence. The alpha value includes the Bonferroni correction.

	Completion Time	Distance Ratio	Settling Time	Settling Distance
ITP vs ITR	**1.11E-07**	0.908	0.788	0.919
ITP vs IMP	**4.07E-09**	**9.75E-07**	**6.64E-09**	**4.40E-09**
ITP vs IMR	**4.53E-09**	0.0145	0.322	0.752
ITR vs IMP	0.839	**8.03E-09**	**1.05E-07**	**3.82E-09**
ITR vs IMR	0.935	**0.002**	0.243	0.367
IMP vs IMR	0.995	0.0307	**1.09E-04**	**3.26E-08**

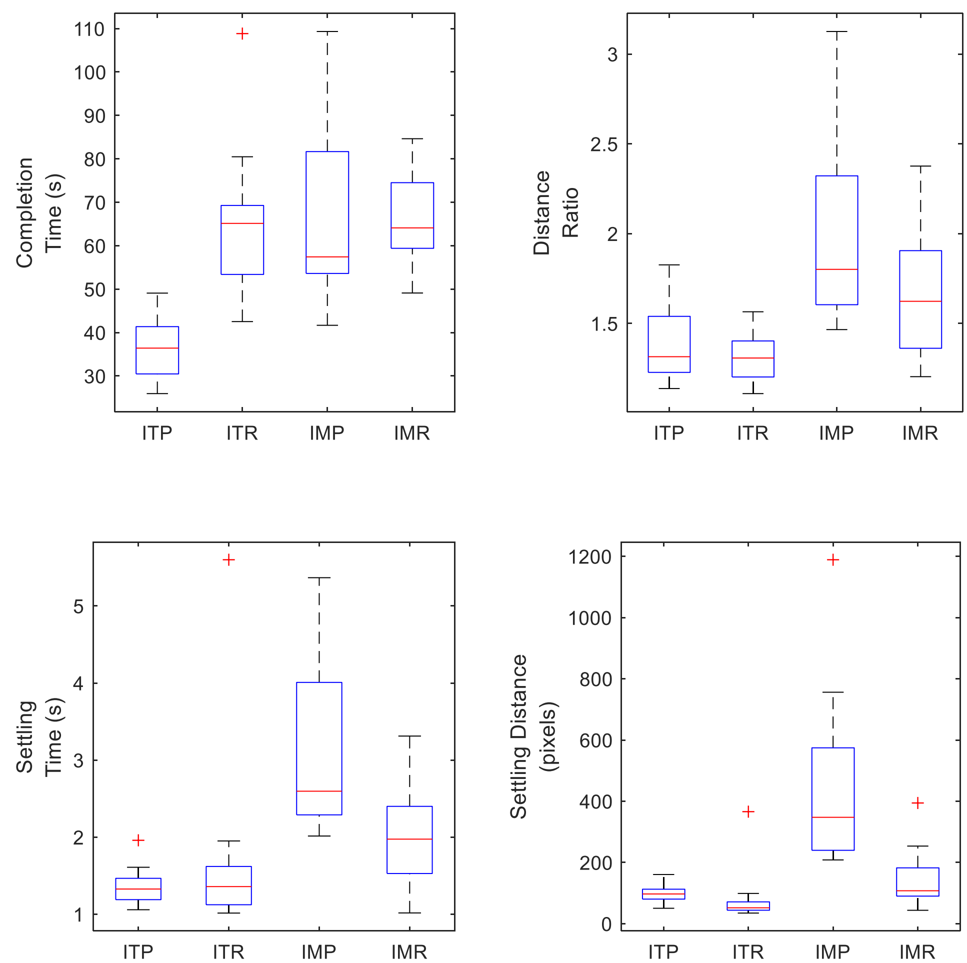

Figure 18. These box plots show the performance of the interfaces for the reaching task from the second session. Lower values indicate better performance for each metric.

Isotonic Position

The ITP interface had a significantly lower completion time than all other interfaces. There was no significant difference in completion time among any of the other interfaces. The ITP interface resulted in significantly lower distance ratios than the IMP interface, but not the other two interfaces.

Isotonic Rate

The ITR interface had significantly lower distance ratios than either of the isometric interfaces.

Isometric Position

The IMP interface had significantly higher settling times and distances than any other interface. The other interfaces were not notably different from each other for the same metrics.

Isometric Rate

IMR was better at stopping than IMP, but there was no significant difference between distance ratios for the isometric interfaces. IMR was not significantly different in stopping behavior relative to ITP or ITR. IMR and ITR were similar in performance, so IMR may be appropriate where rate control is preferred.

Overview

For the isometric interfaces, the relationship between position and rate control is different than for the isotonic interfaces, whose relationship matches previous work [7]. The performance relationships between the interfaces were identical between sessions 1 and 2, but the extra experience subjects had entering session 2 resulted in better performance, so only session two data are included here.

B. Path-Following

Sample trajectories from each interface for the path-following task are shown in Figure 19. Like the reaching task, the recorded trajectory can start from anywhere within the previous target.

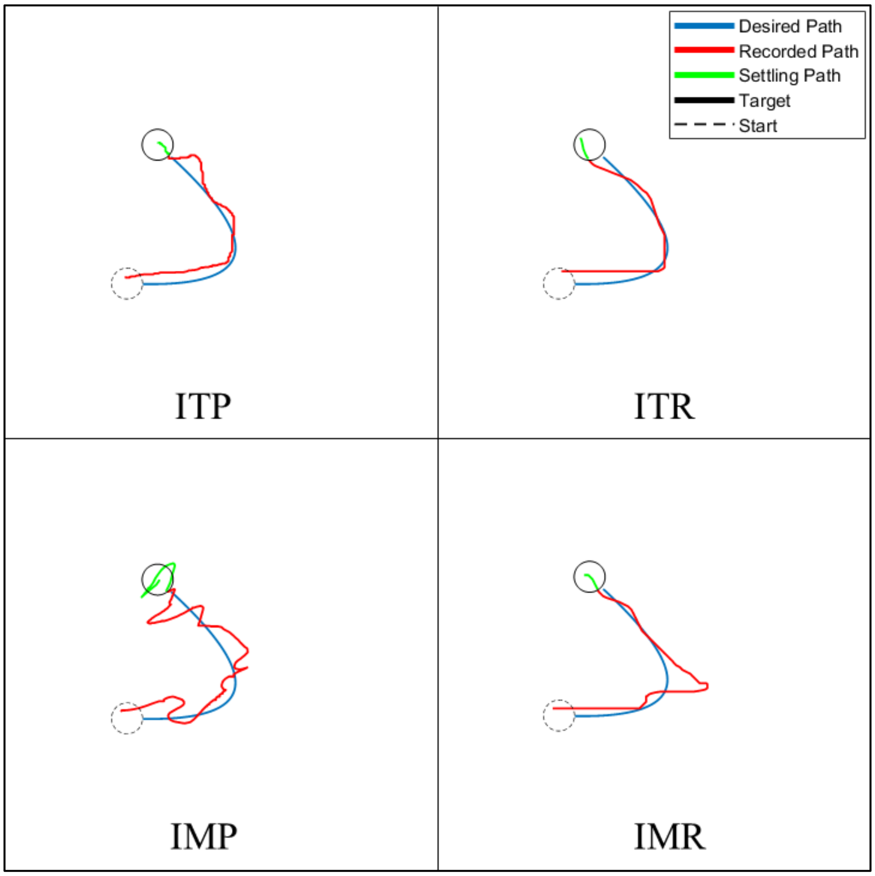

Figure 19. This raw trajectory data gathered from the path-following task shows examples of trajectories from each interface for the same target. The red line is the path traveled by the subject to the target, and the green line is the path traveled after entering the target, shown in black. The previous target is the dashed black line. The blue line is the desired path.

A multiple comparison ANOVA analysis was again used to compare the performance of the interfaces for the path-following task. The Bonferroni correction was used to compensate for multiple comparisons, so the α value for 95% confidence was 0.0083. The p-values from the multiple comparisons are shown in Table 6. Box plots for the path-following task are shown in Figure 20.

Table 6. P-values for the comparison between the interfaces for the path-following task. A value of less than 0.0083 indicates a significant difference at 95% confidence. The alpha value includes the Bonferroni correction.

	Mean Distance	Standardized 2-Norm	Infinity Norm	Completion Time
ITP vs ITR	0.961	0.998	1.00	**0.0028**
ITP vs IMP	**5.43E-09**	**9.28E-09**	**5.30E-09**	0.913
ITP vs IMR	0.0183	0.0387	0.011	**7.60E-04**
ITR vs IMP	**1.47E-08**	**1.46E-08**	**5.43E-09**	0.0185
ITR vs IMR	0.0634	0.0593	0.0113	0.977
IMP vs IMR	**1.40E-04**	**1.53E-04**	**2.56E-04**	**0.0059**

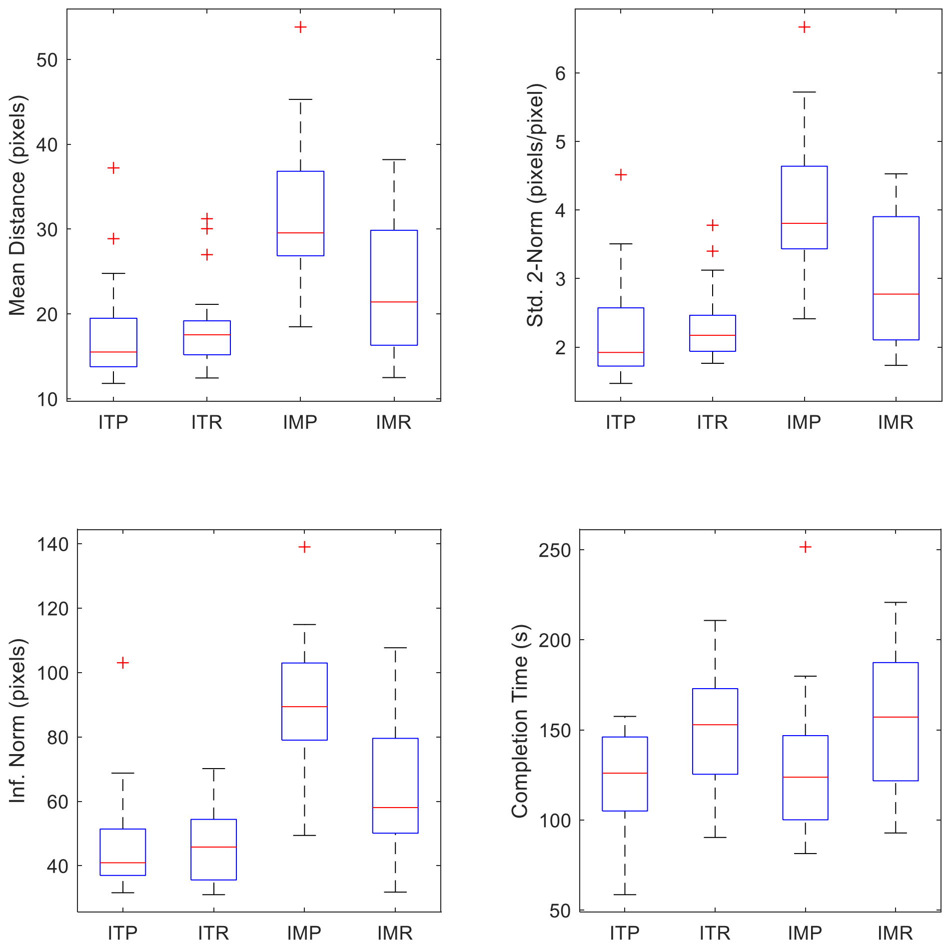

Figure 20. These box plots show the performance difference between the interfaces for the path-following task from the second session. A negative value indicates better performance for each metric.

Isotonic Position

ITP had significantly faster completion times than ITR and IMR. Although ITP was faster than ITR, it performed at the same level for all other metrics.

Isotonic Rate

ITR was significantly better than ITP for all metrics except completion time. ITR and IMR showed no statistically significant differences for any metric for the path-following task.

Isometric Position

For the mean distance and the infinity-norm, the IMP interface was significantly outperformed by every other interface, and there was no statistically significant difference between the other three interfaces for the same metrics. ITP had a significantly lower completion time than either ITR or IMR, but because the path-following task emphasized accuracy over speed, both ITR and IMR were considered better for path-following.

Isometric Rate

IMR exhibited no significant differences from ITR, and it was better than IMP for all metrics except for completion time.

Overview

ITP and ITR had approximately equivalent performance, although ITP is faster. IMP is inferior in all metrics except completion time. IMR is better than IMP and is not significantly different from ITR.

Subjects often verbally indicated that the IMP interface was difficult to use, and most stated that the easiest to use was the ITP interface. From the survey results, the most preferred interface was ITP, followed by ITR, then IMR, and finally IMP. The average scores from the preference survey results and the modified NASA TLX survey results are listed in Figure 21 and Figure 22, respectively. The means and standard deviations of both tasks, and the survey results, are listed in Appendix E.

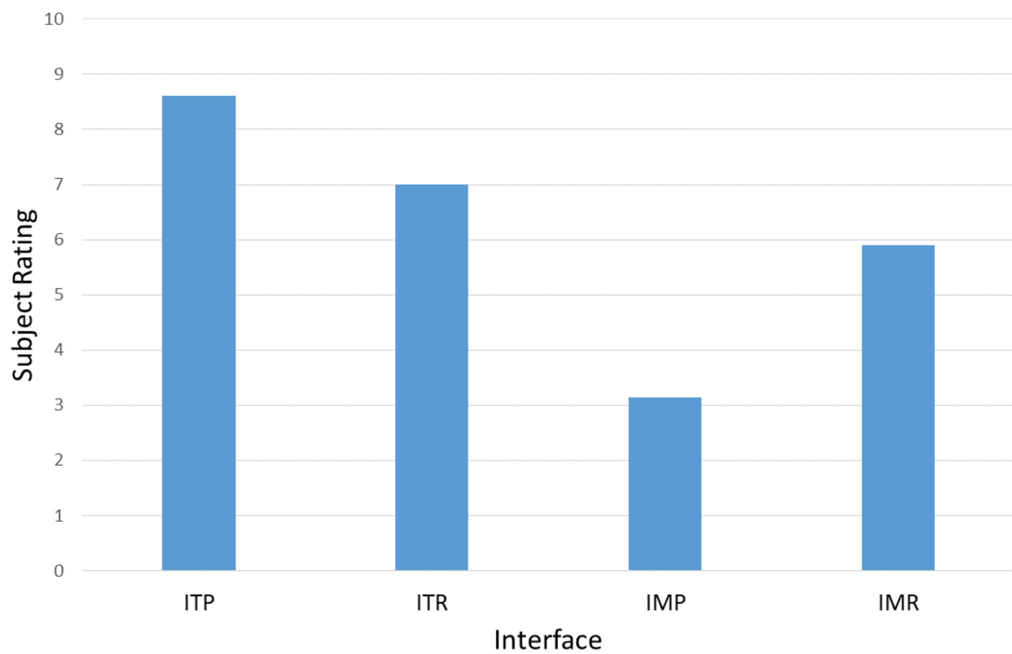

Figure 21. Subject preferences for each interface. ITP is isotonic position, ITR is isotonic rate, IMP is isometric position, and IMR is isometric rate. A higher score corresponds to a stronger preference for the interface.

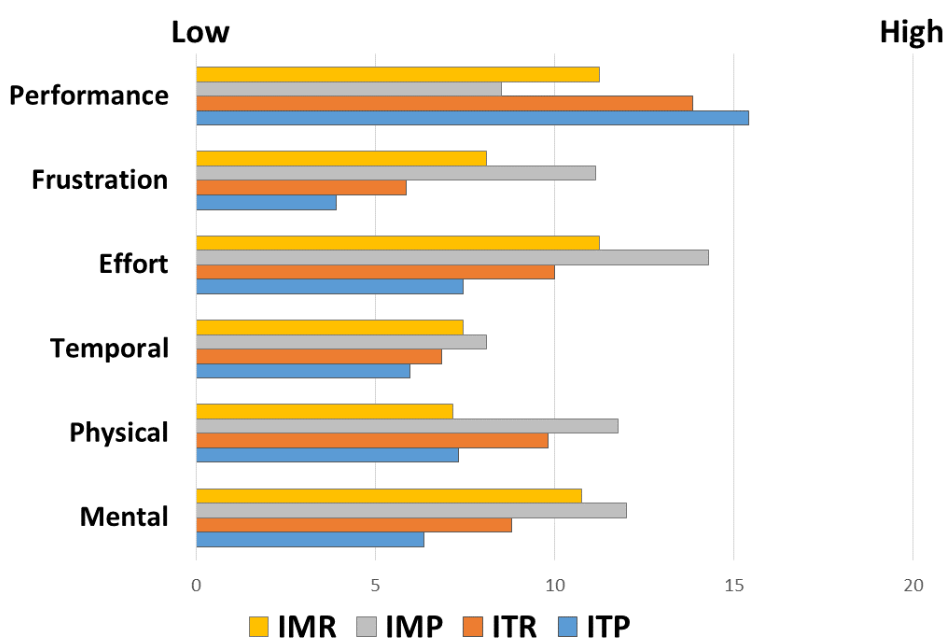

Figure 22. NASA Task Load Index survey results for each interface. ITP is isotonic position, ITR is isotonic rate, IMP is isometric position, and IMR is isometric rate. Lower values are better for all metrics except performance.

The isotonic interfaces generally performed better than the isometric interfaces. Although rate control resulted in longer completion times, the trajectories were much smoother than those of position control for both interfaces. Although, there was no metric for how smooth the trajectories were; it was simply a qualitative observation.

4.5. Summary

The ITP interface achieved the best completion times and comparable, and sometimes better, performance to the other interfaces for the reaching task. While it had statistically similar performance to the rate control interfaces for the path following task, it did so in significantly less time. Additionally, the survey results indicated that the ITP interface was the easiest and most intuitive interface. For the isotonic interface, position control also showed improvement relative to rate control with regard to the stopping behavior, compared to the results from Dougherty's work [7]. This provides further evidence of the benefits of additional friction

The ITP interface would generally be a good choice for real-world applications. If the amount of time taken is not an issue, smoother trajectories are more desirable, and/or the workspace is large, then rate control would be a good choice. Based on the results, IMR is not much worse than ITR, so if rate control is a preferred option, either interface would be a good option. However, a downside of both isometric interfaces is that they require the foot to be strapped onto the interface. Being strapped in makes it much more susceptible to unwanted, sudden movements, whereas the isotonic interfaces allowed users to disengage from the interface easily.

The experiment in the next section used the isotonic position interface because it is intuitive, performs well, and needs little physical effort from the user. The interface needed to be easy to use because a human user had to control a robotic arm and coordinate its motion with their hands.

5. THIRD EXPERIMENT: COORDINATING WITH A FOOT-CONTROLLED SRL

The goal of the experiment in this section was to determine if it is possible for people to use a foot interface to control an SRL and coordinate its movement with their hands. After developing and comparing a variety of interfaces, both isotonic and isometric, an isotonic position control interface was chosen to control a Sawyer robot. The isotonic position interface with friction was easy to control, and could consistently make accurate, small adjustments. Coordinating with an SRL can potentially eliminate the need for partner while enabling the user to perform at a level higher than they could by themselves. The path-following task in the previous sections tested the ability to make fine adjustments, which would be a good way to evaluate the level of coordination. Path-following was used for a three-handed task in this experiment because it requires a high amount of coordination. Subjects controlled an SRL to assist with a path-following task. Robot assistance significantly improved user performance for the task, and as the difficulty of the task increased, the performance of the robot became closer to that of two users than it did of one solo user.

5.1. Experiment

The purpose of this experiment was to evaluate how well a person could coordinate a supernumerary robotic arm with their hands by using their foot. The foot interface used was the isotonic position interface with friction, as described in Section 3.2. A subject's performance was compared with how well they could complete the task with a second human user, and by themselves.

The task was to move a washer along a series of different paths along a tabletop. The idea for this task came from an experiment done by Sathyan and Ma [27]. There were three strings tied to the washer, and the strings were run through three equally spaced holes around the edge of the table. By pulling the strings the washer could be moved along the table. All three strings were necessary to navigate the full workspace, which was a 12-inch diameter circle. Figure 23 shows the washer moving along a path. The task could be completed with two hands, but there were three independent single degrees of freedom (DOFs) to control, so having assistance made the task much easier. The dorsiflexion-plantarflexion DOF of the foot interface controlled one translational DOF of the robot since the string only needed to be tightened or relaxed.

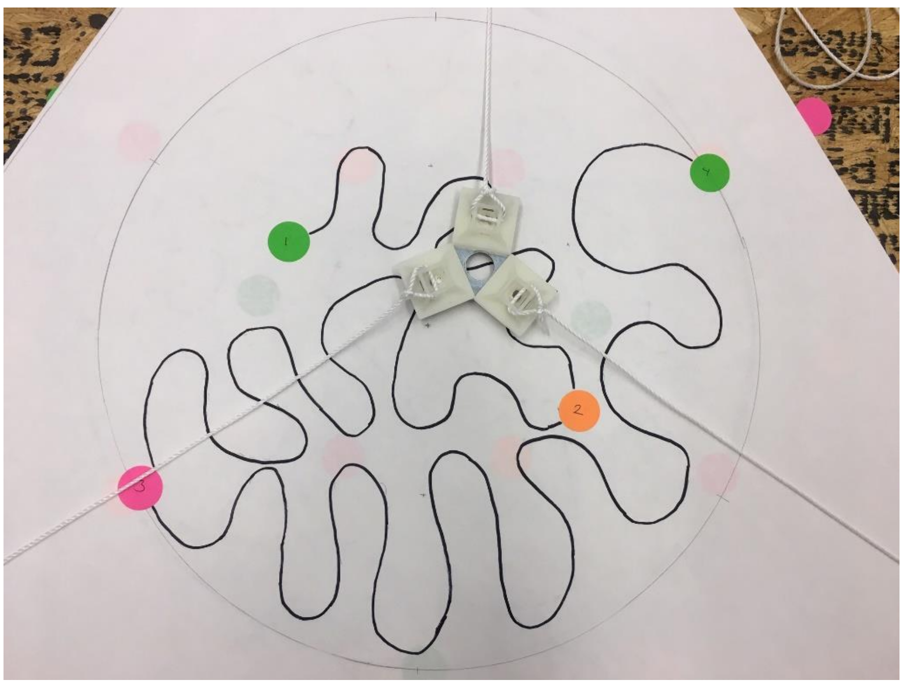

Figure 23. The three strings were used to move the washer along the desired path. If the path left the viewing window of the washer then the subject had to restart the path.

Subjects completed the task with three combinations of control: solo, assisted by a human partner, and assisted by the robot. The order in which subjects completed these combinations was randomized and equally distributed, as can be seen in Table 7. During the sessions with human partners, both subjects were free to communicate. Solo users had to walk around the table and manipulate two strings at a time to complete the task, while users with a partner or users controlling the robot could stay in one spot and reach the full workspace. The robot was calibrated to move the full diameter of the circle with the full range of motion of the isotonic interface. Figure 24 shows a human user working with the robot.

Table 7. Experiment order distribution for balanced data. Subject pairs would both do the same order.

	Session Order		
Pair 1	Solo	Robot	Partner
Pair 2	Robot	Partner	Solo
Pair 3	Partner	Solo	Robot
Pair 4	Solo	Partner	Robot
Pair 5	Robot	Solo	Partner
Pair 6	Partner	Robot	Solo

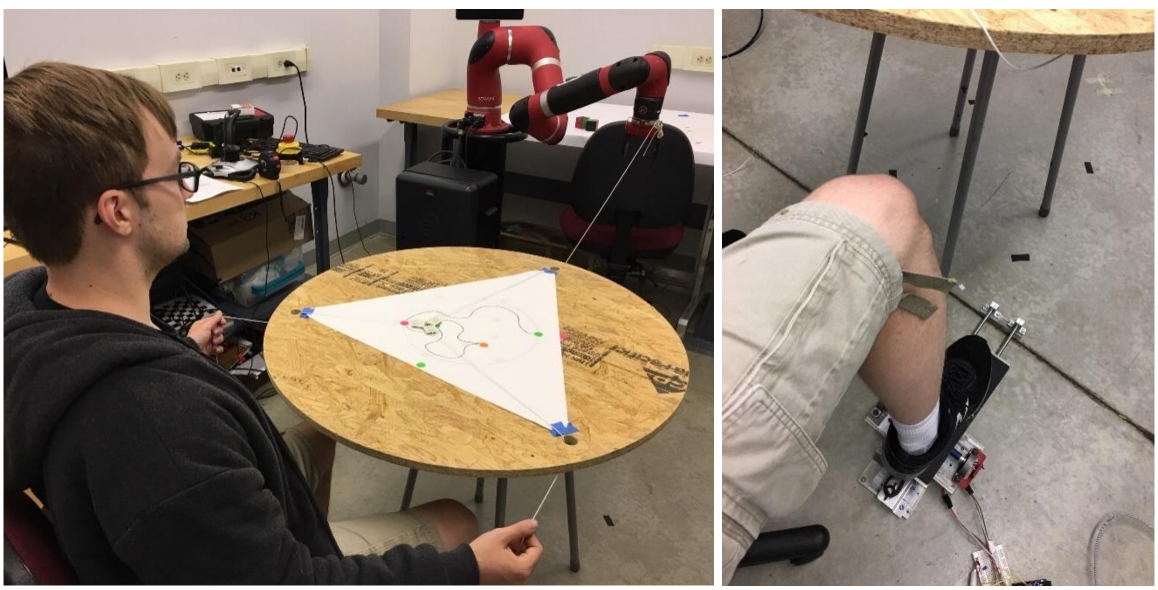

Figure 24. Robot-assisted operation via foot control. The subject holds two strings while the robot controls the third string.

All subjects were given two minutes of practice for every combination of control. User performance was evaluated based on how long subjects took to navigate the paths. The path had to remain visible in the hole of the washer. Otherwise subjects were told to head back to the start point and retry. This was done to provide a measure of the frequency of error, where an error was defined as leaving the path. If they had to restart, then the timer for that path was reset, but the number of retries was recorded. For consistent time recording, the subjects were told to count down before beginning to move along the paths so that the timer started as soon as they started moving. The timer was stopped as soon as the colored target completely filled the washer viewing window. Upon completing all paths with a given input method, subjects filled out a survey, which rated the ease of use, level of effort, and amount of frustration they experienced with that input method. The survey is listed in Appendix H.

There were three difficulty levels: easy, medium, and hard. Each level had three paths: short, medium, and long. Multiple difficulties were included so that any performance differences that might occur on an easier difficulty would become more pronounced on a harder difficulty. The multiple levels also helped to show when robot assistance becomes beneficial. Figure 25 shows the three different difficulty path sets. Subjects started with the easy difficulty, then moved up in difficulty as they completed each set. The short path was between the first two points, the medium path was between the second and third points, and the hard path was between the third and fourth points.

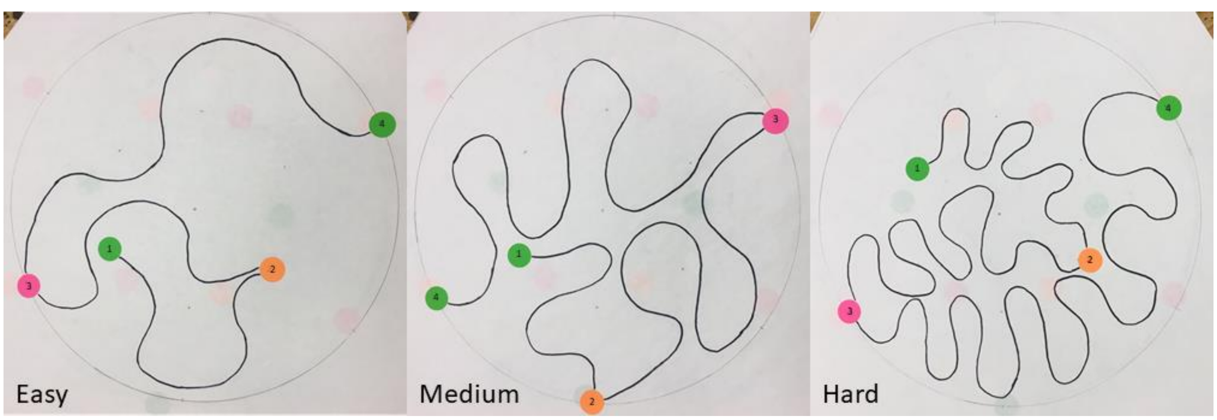

Figure 25. The three difficulty levels for the three-handed path-following task. Each difficulty had three path lengths: short, medium, and long. The subject would always sit positioned towards the bottom of the picture.

During the experiment, the subject always sat in the same location for both the robot session and the partner session, and the robot/partner was positioned on the opposite side of the table. For the partner sessions, the participant controlling two strings was the one whose times were being recorded. Because subjects were scheduled in pairs, they would participate in the partner session twice. Once while controlling two strings, and once while controlling one string. No significant differences were noted from subjects who were recorded second. Twelve participants were recruited for this study: 11 male, 1 female. The average age of participants was 26.1 years. 11 subjects were right-foot dominant, 1 was left-foot dominant.

5.2. Results and Discussion

A multiple comparison ANOVA analysis with the Bonferroni correction was used to compare the relative performances of solo operation with robot assistance, and robot assistance with human assistance. Solo operation was not compared with partner operation because the purpose of the experiment was investigating how robot assistance compares with other input methods. The ANOVA analysis took into account subject dependence, so performance from one subject would not be compared to data from another subject. P-values of the analysis for the completion times are shown in Table 8. Box plots of the completion times for each difficulty and control method are included in Figure 26, as well as the completion time for all paths combined. The average number of retries was 1.89 for the solo session, 1.50 for the robot-assisted session, and 0.7 for the human partner session.

Table 8. P-values for the comparison of completion times between robot-assisted operation and the other two control methods. A value of less than 0.025 indicates a significant difference at 95% confidence. Significant values are shown in bold. The alpha value includes the Bonferroni correction.

	Easy	Medium	Hard	Total
Solo vs. Robot	0.208	**5.81E-09**	**1.60E-09**	**0.985E-08**
Robot vs. Partner	0.565	0.6129	0.838	0.660

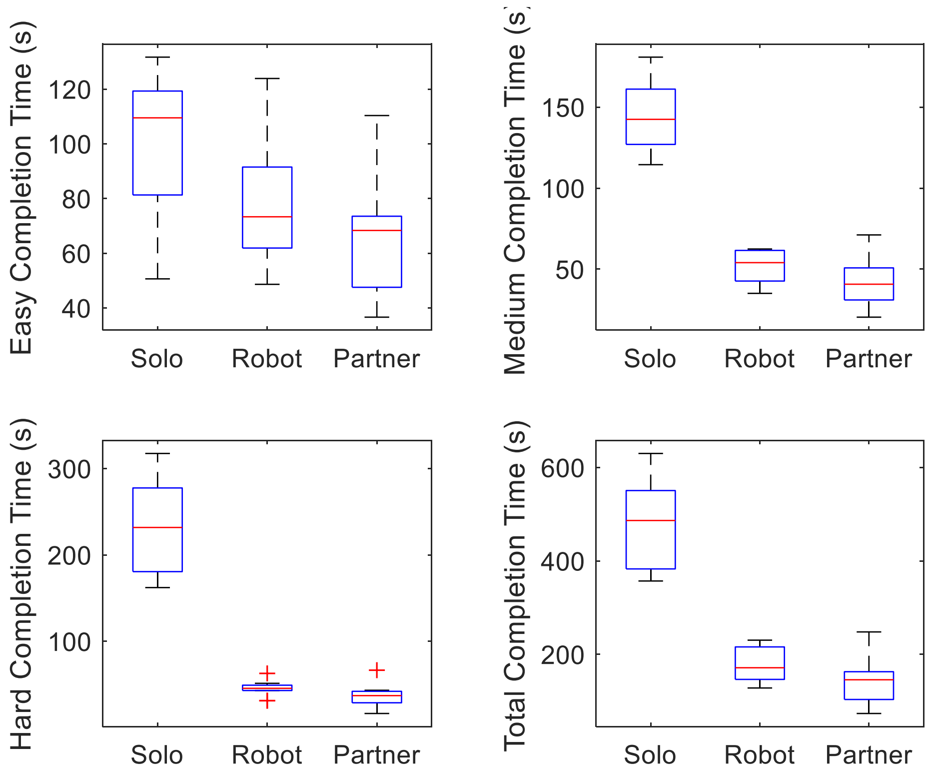

Figure 26. Box plots of the completion times for each difficulty level and input method. Robot assistance is faster than solo operation, and partner assistance was not significantly faster than robot assistance.

The differences in completion times were also examined. This was to check whether robot-assisted performance was more similar to solo performance or partnered performance. A paired t-test was used to test for significance, since only one comparison was being made, which was comparing the difference between the robot and solo completion times with the difference between the robot and partner completion times. Like the ANOVA analysis, the paired t-test took subject dependence into account. The p-values for the completion time differences are shown in Table 9. The box plots in Figure 27 show the completion time difference between solo operation and the robot assistance compared with the difference between robot assistance and partner assistance. The box plots showing the relative difference in completion times between the solo vs. robot and robot vs. partner sessions are captured in Appendix I.

Table 9. P-values for the comparison of completion time differences between robot-assisted operation and the other two control methods. A value of less than 0.05 indicates a significant difference at 95% confidence. Significant values are shown in bold.

	Easy	Medium	Hard	Total
Solo and Robot vs. Robot and Partner	0.5926	**6.17E-05**	**7.85E-07**	**4.44E-06**

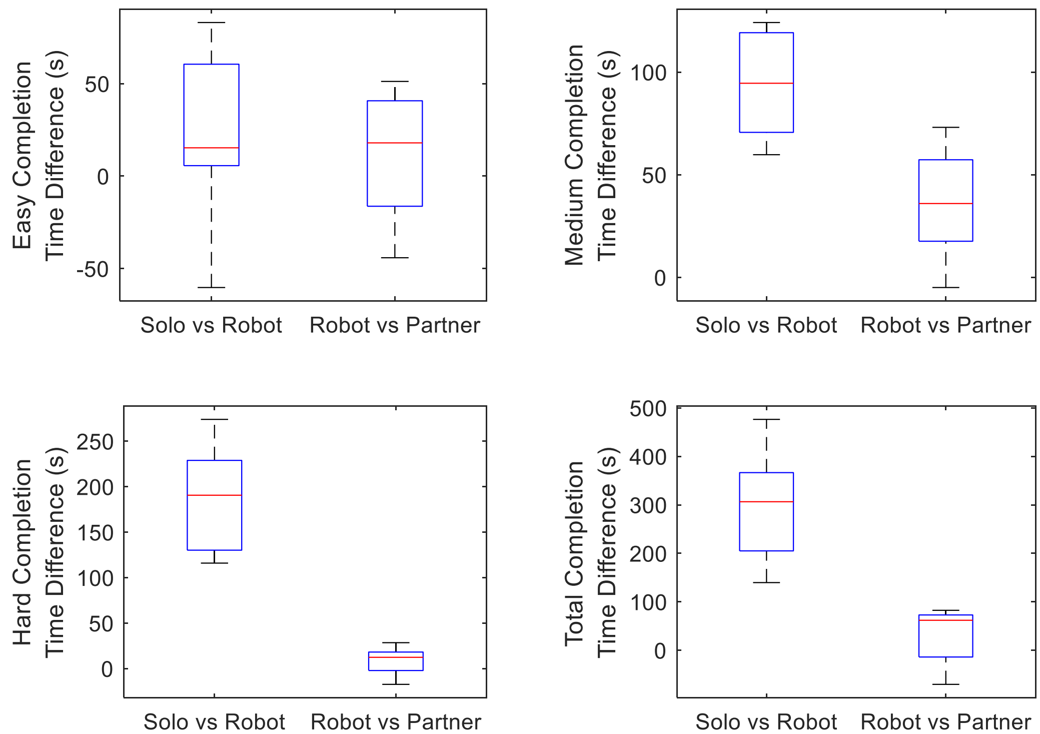

Figure 27. Box plots for the differences in completion time for each difficulty level. Medium, hard, and total completion time differences are much smaller between robot assistance and partner assistance than they are between solo operation and robot assistance.

All twelve participants were asked to complete a survey after finishing each input method. The average scores from the post-completion survey results are shown in Figure 28. No differences were noted from demographic variations.

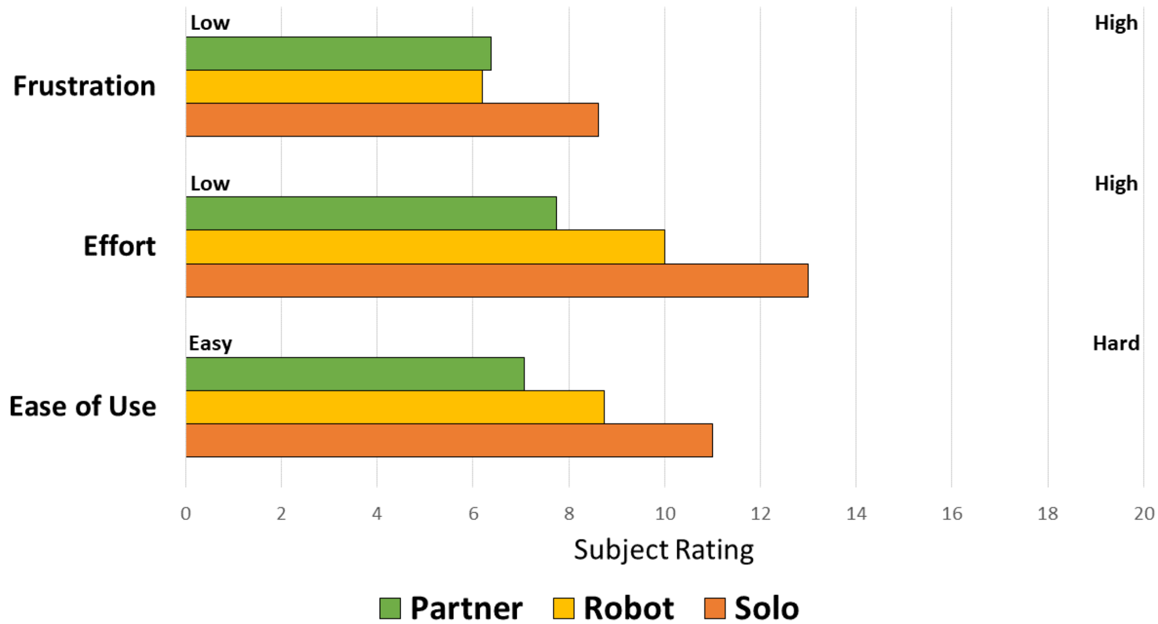

Figure 28. Survey results for each input method. Lower values are better for all metrics.

There was no significant difference between the robot-assisted operation and the other input methods for the easy difficulty level. For the medium and hard difficulties, robot assistance was significantly faster than solo operation, and partner assistance was significantly faster than robot assistance. This also held true for the overall completion time. The ease of use for the robot assistance was only slightly lower than that of the solo operation, but it had lower rated required effort and frustration.

With every difficulty past easy, there was no statistically significant difference in performance between the robot-assisted session and the human partner session. The completion time differences are consistent with the performance levels. Both comparisons show that for any difficulty greater than easy, robot assistance was not statistically different from human assistance, and was significantly better than solo operation. Survey results also indicated that subjects preferred using the robot instead of working by themselves, and the robot was slightly less frustrating to coordinate compared to a second human user.

5.3. Summary

Controlling a robot with the foot to help with a three-handed task resulted in significant improvement over completing the same task alone. Robot-assisted operation proved to be statistically indistinguishable from the performance of human-assisted operation, and it was significantly better than solo operation with more difficult motions. Subjects also preferred using the robot over completing the task by themselves, although for almost all users having a human partner was the most preferred control method.

In real-world applications, having a robot assist a user eliminates the need for a second person to complete a task. Also, depending on the workspace, a robot arm may be able to reach areas that a second user cannot reach, or handle a material that is too dangerous to handle safely otherwise.

This experiment showed that human users could reliably use their foot to control a robot and coordinate the motion of the robot with their hands. With the robot assistance, users performed at a significantly better level than they did by themselves. One of the limitations of this experiment is that the task is relatively simple and does not directly relate to a specific application. Additionally, the robot only moved in 1 DOF. Adding higher DOFs should be investigated, as that would likely present a better idea of how much a foot-controlled SRL can benefit a human user.

6. CONCLUSIONS

The first two experiments established some of the design principles that make an intuitive and high-performing foot interface. The results from the first experiment show that adding friction to an isotonic interface improves the user's ability to stop and hold position without affecting their dynamic performance, and also allows the user to remove their foot from the interface without changing the input. The second experiment shows that an isotonic position control interface with friction is the overall best interface to use for two-dimensional positioning tasks. Isotonic rate can achieve the same level of performance, but not as quickly as isotonic position. Isometric rate is comparable to isotonic rate, so if rate control is desired, then either interface would make a viable option, although the isometric interface does not allow the user to remove their foot. The isometric rate interface outperforms isometric position, which is the opposite relationship compared to the isotonic interfaces, likely because holding a constant force to maintain a position is difficult and fatiguing for a human user.

The final experiment shows that people can coordinate well with a foot-controlled SRL while using their hands. With more difficult tasks, the performance of SRL assistance was the same as that of two human users, and significantly better than a solo user. Users also preferred to use the robot instead of working by themselves. Controlling an SRL with the foot clearly improves the performance of a single user, and robot assistance brings the capability of a single user to the level of capability of two users.

7. FUTURE WORK

Future work should investigate larger workspaces. The workspaces in all three experiments were relatively small, so even though isotonic position control was well suited to the tasks, it may become too sensitive as the size of the workspace increases. If isotonic position control does become too sensitive, then one of the rate interfaces would be a good option.

Generally, isotonic interfaces were more intuitive than isometric interfaces. With the isotonic interfaces, subjects learned how to use them well very quickly, showing little change from the first to the second session. The isometric interface showed greater improvement from the first to the second session, but user performance was still highly varied, so future experiments can explore the effects of more practice. It is possible that the gap in performance between isotonic and isometric could be eliminated with additional practice, particularly for rate control.

For inexperienced users, controlling an SRL with an isotonic interface would be much easier, so future research should strongly consider isotonic interfaces where SRLs are involved.

In the final experiment, only one DOF of the robot was controlled by the foot. Additional DOFs can be added and more complex tasks can be tested. The isometric interfaces are well suited to adding higher DOFs since the interface does not need to change to add more DOFs.

The next step for the foot-controlled robot would be to add more DOFs. The isotonic interface in the third experiment had the potential for 2DOFs but only used one, so another experiment could modify the task to use both. Adding more DOFs to the isotonic interface would get more complicated, as the interface would need to increase in complexity, and translational movements would begin to face the fatigue issues seen in Dougherty's work [7]. The isometric interface would not need to change with the addition of more DOFs, but users would need to practice more to use it proficiently. The isometric interface also does not let users disengage from the interface easily, whereas the isotonic one does.

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APPENDICES

APPENDIX A

The modified NASA TLX Survey used in experiments 1 and 2.

Interface:

Please rate the following by marking the appropriate line

Mental Demand:

How much mental activity was required?

Very Low Very High

Physical Demand:

How much physical activity was required?

Very Low Very High

Temporal Demand:

How hurried or rushed was the pace of the task?

Very Low Very High

Performance:

How successful were you in your task?

Poor Good

Effort:

How hard did you have to work to accomplish your level of performance?

Very Low Very High

Frustration:

How irritated, stressed, and annoyed were you versus content, relaxed and complacent?

Very Low Frustration Very High Frustration

Comments regarding input device and/or control?

APPENDIX B

Examples of the path types in the path-following task.

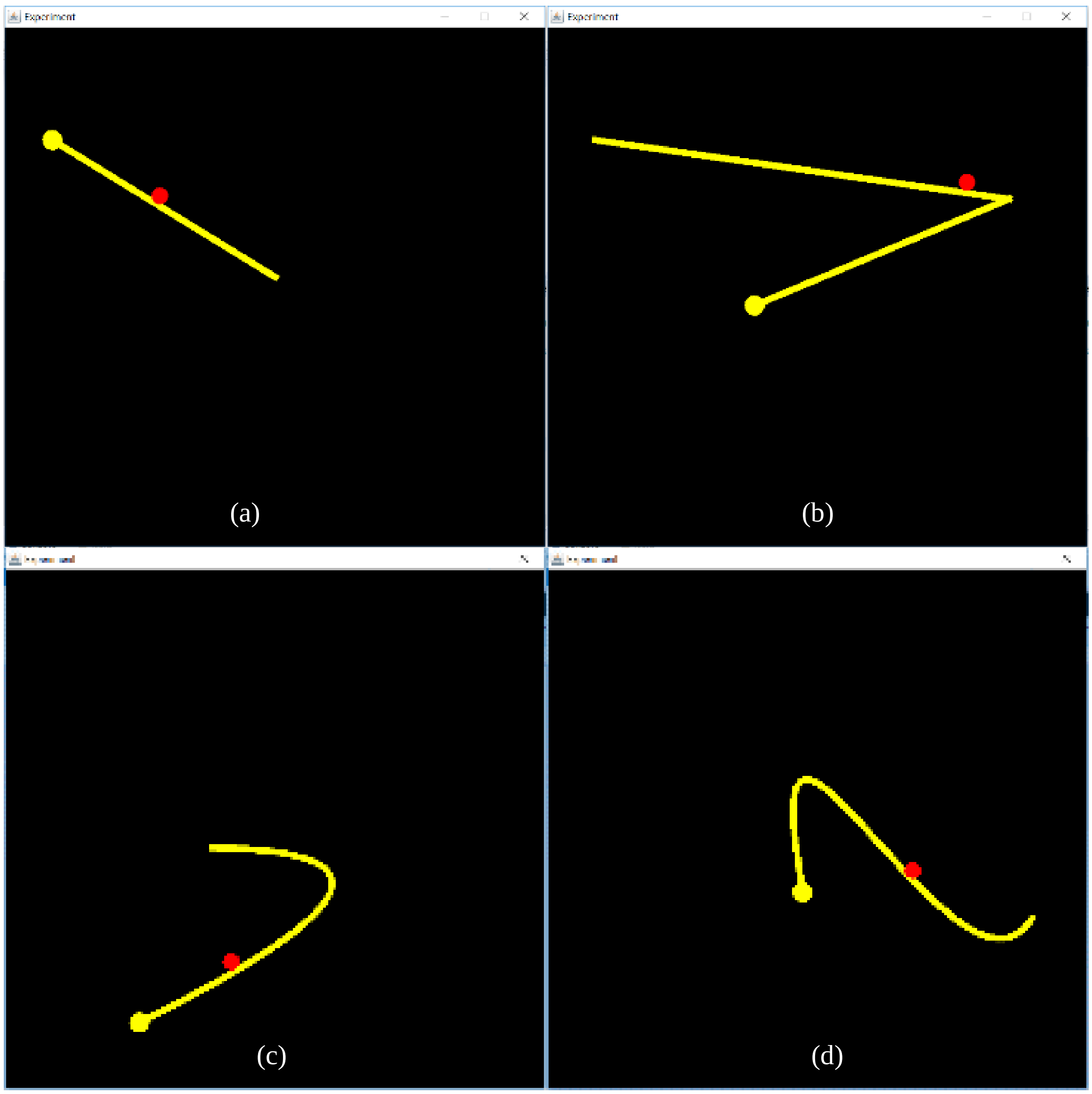

Figure B.1: Examples of each type of path for the path-following task. Four path types were used: straight line (a), straight corner (b), quadratic (c), and cubic (d). There were five instances of each type of path in the first experiment, and twelve of each in the second experiment.

APPENDIX C

Box plots for the performance differences in experiment 1.

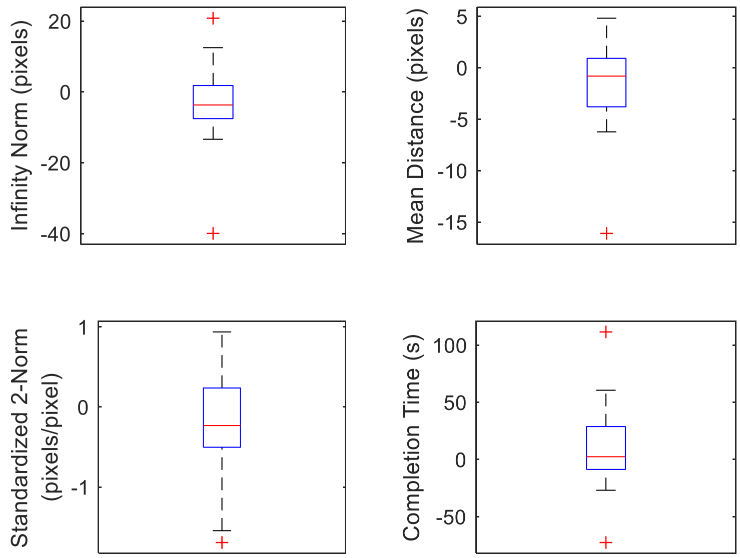

Figure C.1: These box plots show the performance differences of the friction interface and no friction interface for the path-following task in the first experiment. A value of zero indicates no difference between the interfaces. A negative value indicates better performance with the friction interface. A positive value indicates better performance with the no friction interface.

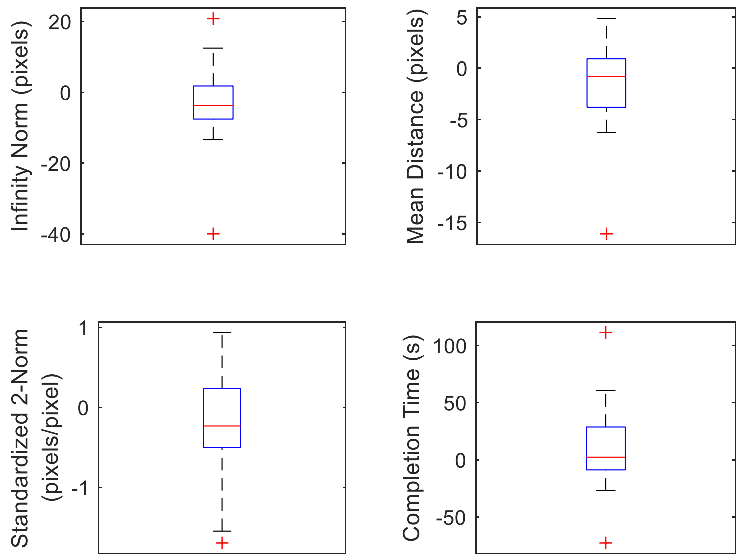

Figure C.2: These box plots show the performance differences of the friction interface and no friction interface for the path-following task in the first experiment. A value of zero indicates no difference between the interfaces. A negative value indicates better performance with the friction interface. A positive value indicates better performance with the no friction interface.

APPENDIX D

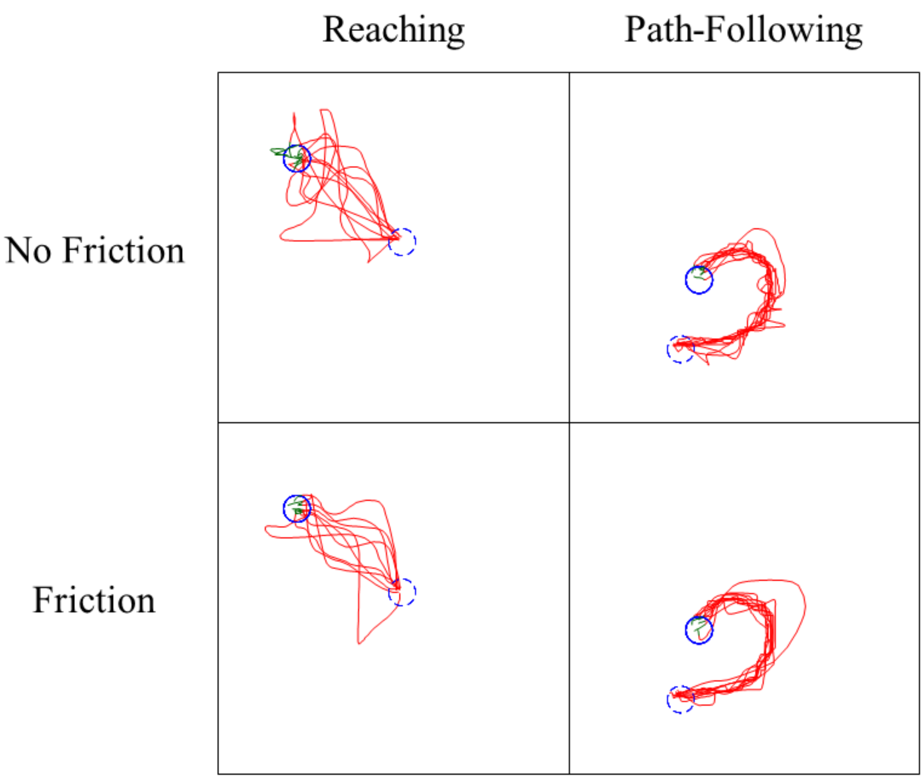

Figure D.1: Overlaid trajectories for both tasks from all subjects in the first experiment.

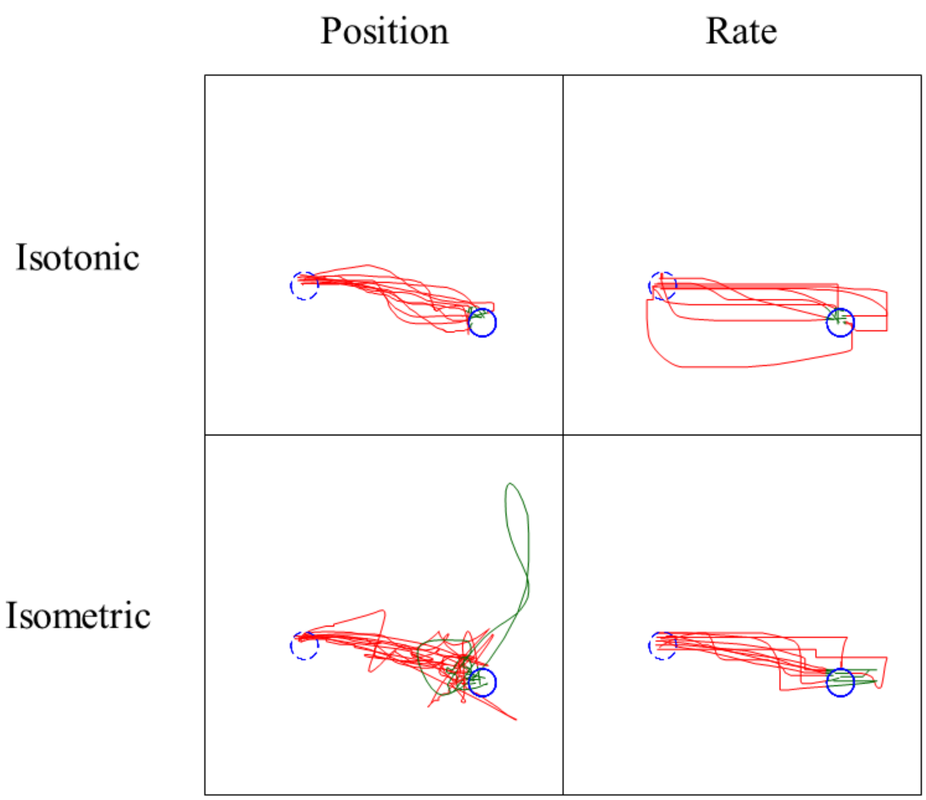

Figure D.2: Overlaid reaching trajectories from all subjects in the second experiment.

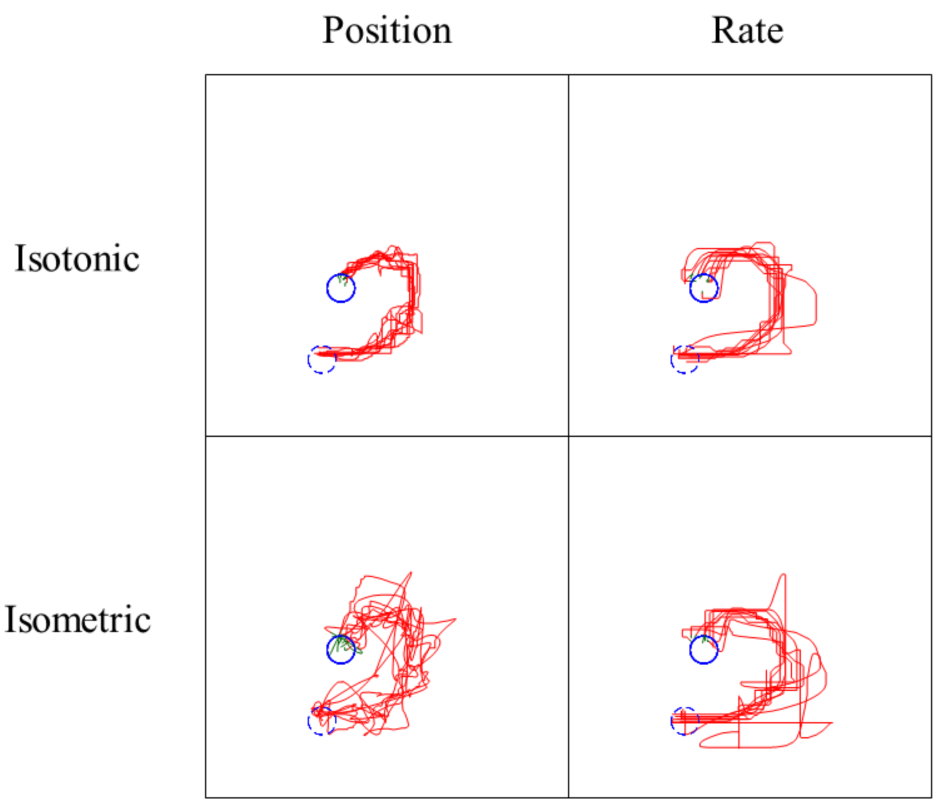

Figure D.3: Overlaid path-following trajectories from all subjects in the second experiment.

APPENDIX E

The mean and standard deviation for the metrics and NASA TLX in the first and second experiments.

Table E.1: The mean and standard deviation of the performance of both interfaces for the reaching and path-following tasks in the first experiment.

		Friction		No Friction	
		Mean	STD	Mean	STD
Reaching	Completion Time (s)	53.248	6.675	53.272	6.539
	Distance Ratio	1.318	0.104	1.310	0.132
	Settling Distance (pixels)	109.145	26.748	142.829	51.797
	Settling Time (s)	1.283	0.171	1.353	0.177
Path-Following	Completion Time (s)	182.118	70.833	172.984	83.572
	Mean Distance (pixels)	15.768	4.262	17.353	5.945
	Infinity Norm (pixels)	41.088	12.306	43.838	13.576
	Standardized 2-Norm (pixels/pixel)	2.283	0.552	2.523	0.910

Table E.2: The mean and standard deviation of the NASA TLX results from the first experiment.

		Friction		No Friction	
		Mean	STD	Mean	STD
Reaching	Mental	6.8	4.33	7.85	4.98
	Physical	6.1	4.05	7	4.08
	Temporal	6.9	5.18	7.9	5.17
	Performance	15.15	3.59	15.45	3.14
	Effort	7.6	4.07	9.2	4.47
	Frustration	4.5	3.05	5.7	4.38
Path-Following	Mental	12	4.50	13.15	4.32
	Physical	9.25	3.79	11	5.02
	Temporal	6.1	3.42	8.45	7.24
	Performance	11.45	2.93	10.3	3.64
	Effort	12.45	3.68	12.3	4.59
	Frustration	8.1	4.16	9.2	3.79

Table E.3: The mean and standard deviation of the performance metrics for the reaching and path-following tasks in the second experiment.

		Isotonic Position		Isotonic Rate		Isometric Position		Isometric Rate	
		Mean	STD	Mean	STD	Mean	STD	Mean	STD
Reaching	Completion Time (s)	35.93	6.44	63.64	15.29	66.82	20.19	65.9	9.84
	Distance Ratio	1.38	0.21	1.31	0.14	1.99	0.51	1.70	0.37
	Settling Distance (pixels)	99.20	31.27	72.43	71.14	429.88	255.13	141.00	82.36
	Settling Time (s)	1.35	0.216	1.57	0.99	3.13	1.08	2.02	0.65
Path-Following	Completion Time (s)	122.71	28.85	150.37	33.67	127.63	38.31	153.40	38.39
	Mean Distance (pixels)	17.67	6.41	18.56	5.18	31.49	8.70	23.17	7.74
	Infinity Norm (pixels)	46.78	17.13	46.90	12.83	88.4	22.12	64.34	22.58
	Standardized 2-Norm (pixels/pixel)	2.28	0.78	2.32	0.54	3.99	1.07	2.93	0.96

Table E.4: The mean and standard deviation of the NASA TLX results from the second experiment.

	Isotonic Position		Isotonic Rate		Isometric Position		Isometric Rate	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
Mental	6.35	3.54	8.80	3.89	12.00	4.70	10.75	4.62
Physical	7.30	3.63	9.80	4.27	11.75	4.87	7.15	4.46
Temporal	5.95	4.06	6.85	4.37	8.10	3.68	7.45	4.29
Performance	15.40	3.28	13.85	3.08	8.50	5.01	11.25	4.14
Effort	7.45	4.22	10.00	3.97	14.30	3.10	11.25	3.68
Frustration	3.90	3.14	5.85	4.77	11.15	5.61	8.10	4.73

APPENDIX F

The preference survey used during the second experiment.

Score how well you liked/preferred the given interfaces, with 1 being not at all and 10 being very much.

Isotonic Position

1 2 3 4 5 6 7 8 9 10

Isotonic Rate

1 2 3 4 5 6 7 8 9 10

Isometric Position

1 2 3 4 5 6 7 8 9 10

Isometric Rate

1 2 3 4 5 6 7 8 9 10

APPENDIX G

The results from the first session of the second experiment, and the comparison of the data from both sessions.

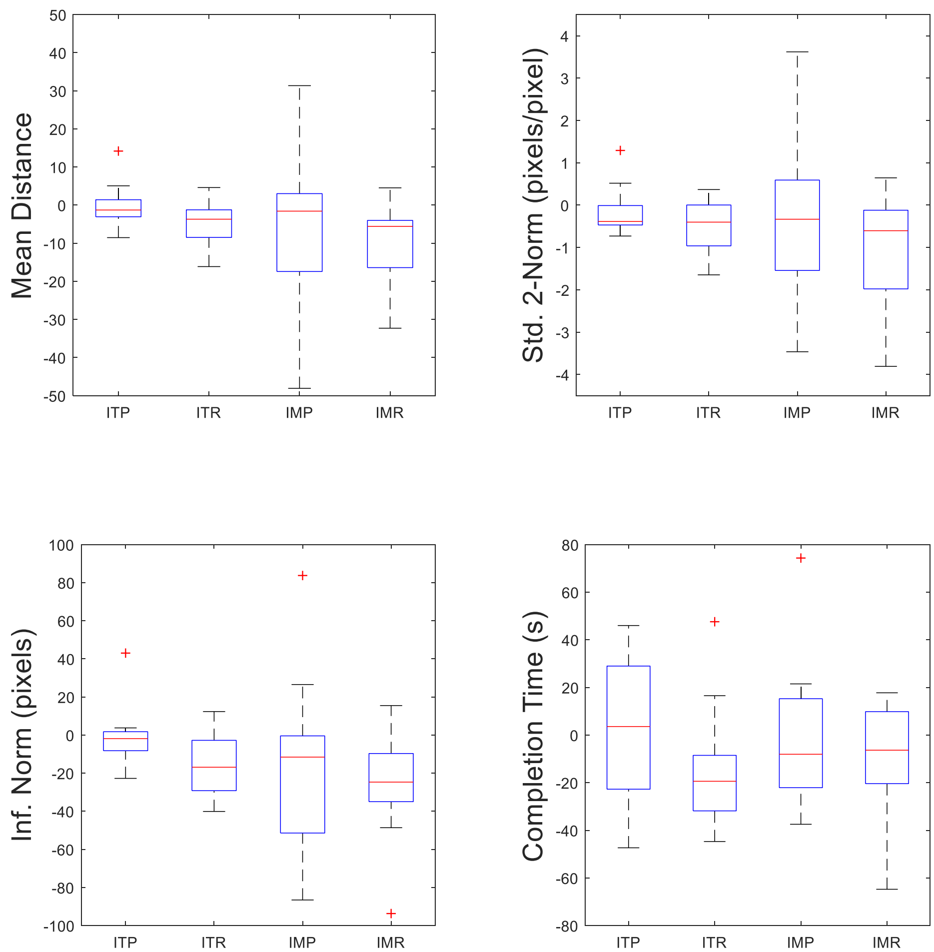

Figure G.1: These box plots show the performance comparison of the interfaces between both sessions of the path-following task. A negative value indicates better performance during the second session.

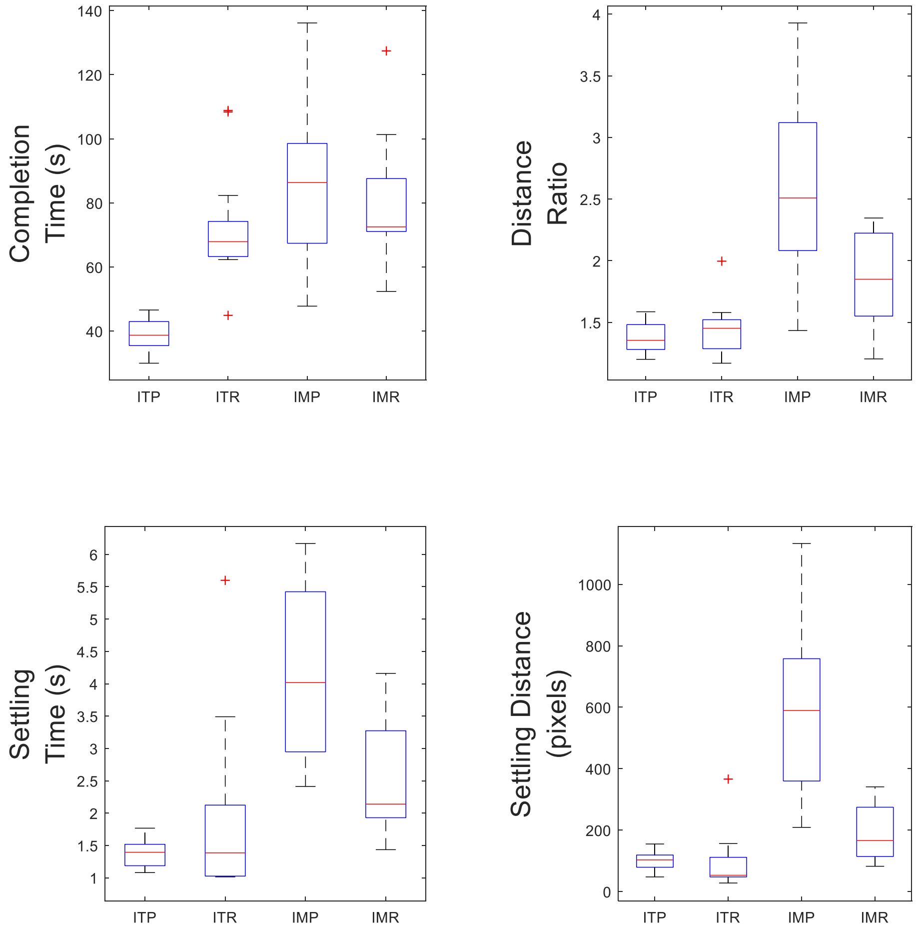

Figure G.2: These box plots show the performance difference of the interfaces for the reaching task from the first session. Lower values indicate better performance for each metric.

Table G.3: P-values for the reaching task for the first session of the second experiment.

	Completion Time	Distance Ratio	Settling Time	Settling Distance
ITP vs ITR	**6.39E-05**	0.964	0.550	1.000
ITP vs IMP	**5.79E-08**	**2.93E-08**	**4.04E-07**	**9.85E-09**
ITP vs IMR	**1.65E-06**	0.015	0.031	0.422
ITR vs IMP	0.111	**1.08E-07**	**2.34E-05**	**9.95E-09**
ITR vs IMR	0.633	0.0465	0.414	0.425
IMP vs IMR	0.673	**4.08E-04**	**0.002**	**6.07E-07**

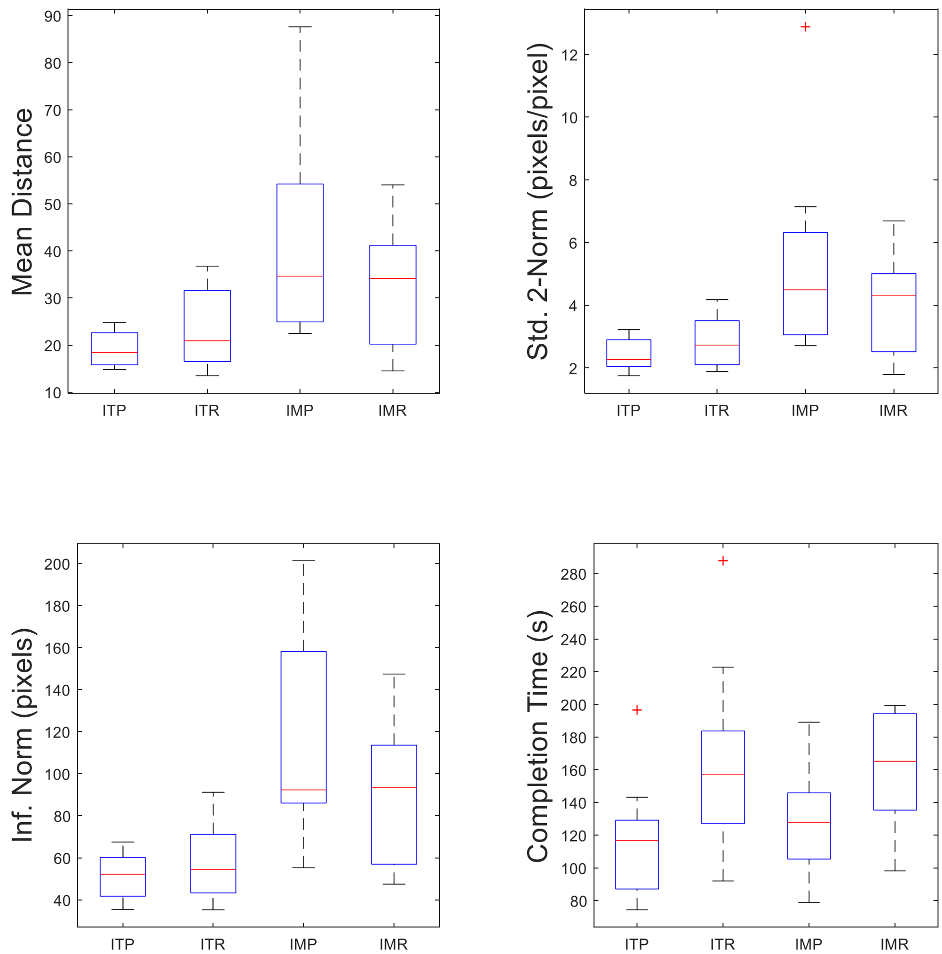

Figure G.4: These box plots show the performance difference between the interfaces for the path-following task from the first session. A negative value indicates better performance for each metric.

Table G.5: P-values for the path-following task for the first session of the second experiment.

	Mean Distance	Standardized 2-Norm	Infinity Norm	Completion Time
ITP vs ITR	0.737	0.910	0.83	**0.001**
ITP vs IMP	**1.84E-05**	**1.26E-04**	**9.74E-07**	0.500
ITP vs IMR	**0.006**	0.037	**0.002**	**0.002**
ITR vs IMP	**4.04E-04**	**9.03E-04**	**1.35E-05**	0.046
ITR vs IMR	0.078	0.155	0.016	0.996
IMP vs IMR	0.210	0.188	0.087	0.077

APPENDIX H

The post-completion survey used in experiment 3.

Circle one:
Solo
Robot
Partner

Please rate the following by marking the appropriate line

Ease of Use:

How easy was it to coordinate movement in the three directions?

Very Easy — Very Difficult

Effort:

How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration:

How irritated, stressed, and annoyed were you versus content, relaxed and complacent?

Very Low Frustration — Very High Frustration

Comments regarding input device and/or control?

APPENDIX I

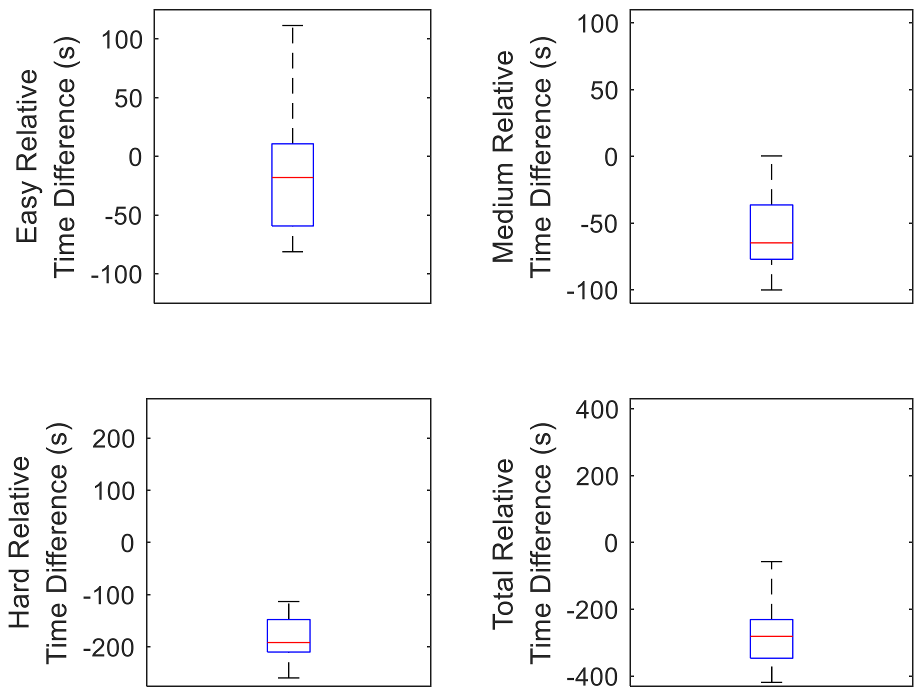

Figure I.1: Relative time differences between the solo vs. robot session and robot vs. partner session. A negative value indicates a smaller difference between the robot vs. partner session than between the solo vs. robot session.