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Foot-Controlled Supernumerary Robotic Arm: Control Methods and Human Abilities

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ABSTRACT

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Foot Controlled Supernumerary Robotic Arm: Control Methods and Human Abilities

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Supernumerary robotic limbs (SRLs) are extra robotic appendages that help a user with various tasks. A challenge with SRLs is how to operate them effectively. One solution is to use the foot to teleoperate the arm, freeing the person to use their arms for other tasks. However, unlike hand interfaces, it is not known how to create effective foot control for robotic teleoperation. A foot interface is developed for an experiment to compare position and rate control with the foot. Position control is shown to be more effective than rate control for 2D positioning tasks. Even if an effective control strategy is implemented, it is currently unknown if a person has the ability to control a robot with their foot while simultaneously using both arms. A second experiment shows that humans can operate an SRL with the foot while performing a task with both hands.

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

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LIST OF ABBREVIATIONS

HRC	Human Robot Collaboration
SRL	Supernumerary Robotic Limb
RH	Rate-Hand
PH	Position-Hand
RF	Rate-Foot
PF	Position-Foot
TLX	Task Load Index

GLOSSARY

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.

Supernumerary – Additional, or excess.

Teleoperation – Method of directly controlling something via an interface.

1. INTRODUCTION

Human robot collaboration (HRC) is an ongoing topic of research where a robot works closely with a human in order to accomplish a goal. A subset of HRC is interaction with a supernumerary robotic limb (SRL). SRLs are robots that assist a user during a task, as if the user has an extra limb. This extra limb has the potential to increase productivity and safety in certain jobs [1]. SRLs have been investigated for applications such as aircraft assembly, robotic surgery, and electronics soldering [1-3]. Research has also been conducted into other SRLs, such as a sixth finger [4]. One of the challenges for all SRLs is how to control them to provide assistance.

Researchers have explored autonomous control [1, 5] as well as direct teleoperation [2] to control SRLs. Autonomous control is particularly challenging because the robot must detect what the human is doing, infer the human's intent, and determine how to provide the appropriate assistance. Direct teleoperation is more feasible for most applications. However, to truly have a robotic third arm, the human must be able to maintain control of their two physical arms. Thus, if an operator can use their foot to control a robot arm, the robot can perform with direct knowledge of the operator's intent, while the operator's arms are free for other tasks. One example of foot control for robotics with hand autonomy includes robotic surgery [2]. The use of foot control for SRLs has been suggested by Wentzel et al., Elahe et al., and Sasaki et al. [2, 3, 6], but little work has been done on how to best create the interface.

The ability of an operator to provide input with the foot and simultaneously perform a task that also involves the hands is a key factor in foot-controlled SRLs. If using a foot-controlled SRL is cognitively or physically too difficult, then the advantage of the extra limb could be lost. While people use their hands and feet to perform tasks simultaneously every day (drive a car, play the drums or piano, dance), foot-controlled SRLs may be more difficult.

Operator ability to use a foot-controlled SRL may be heavily influenced by the control method used. Two common methods are position and rate control. Position control uses the position of the interface to determine the output position. An example of position control is a car steering wheel, where the angle of the tires are related to the position of the steering wheel. Rate control uses the position of the interface to output velocity. An example of rate control is airplane steering, where the position of the controller determines how fast and in which direction the airplane tilts. While the comparison between rate and position control has been explored thoroughly for the hand, it is not well known for the foot.

This thesis explores the comparison between position and rate control for the foot, as well as the ability for an operator to use a foot-controlled SRL to perform a task. To facilitate this goal, a foot interface was designed. The first interface was a foot joystick that was modified from a commercial hand joystick. This interface performed poorly, so a second interface, a planar foot interface, was designed. Both iterations of interface design are shown in Sections 3 and 4, as well as the control method experiments. The comparison is also made between each foot interface and a standard hand interface. This provides a baseline for each experiment, and helps determine the overall effectiveness of the foot interface relative to a comparable hand interface.

Finally, the interface was used with the position control to teleoperate a robotic arm in a task that simultaneously uses both of the operator's hands. This was done to determine if a person can coordinate both hands while operating a robot via foot control. Results show that humans can perform a task using both hands while using a foot-controlled robot arm. This helps establish the feasibility of foot input as a method of controlling an SRL.

2. LITERATURE REVIEW

2.1 Supernumerary Robotic Limbs

Supernumerary Robotic Limbs (SRLs) were originally described by Davenport as "a wearable robot that provides extra limbs to a human worker with the intent of assisting him in manufacturing and various other tasks" [7]. This thesis will focus on a slightly different vision of an SRL. The purpose of assisting a human worker remains the same, but the SRL will not be worn by the operator. Instead, the robot will just operate in the same workspace as the human. This may decrease perceived ownership of the arm as an extra limb, however, it allows any human-safe robot to be used without modification.

One use of worn SRLs is explained by Parietti and Asada as a pair of robot arms that provide stability to an aircraft fuselage worker [1]. The two arms can work together to provide static equilibrium for the user while the user leans into the wall being worked on. This decreases the number of workers needed as well as the overall effort required to complete the task. Vatsal and Hoffman discuss more cases where having an extra robotic forearm would be beneficial [8]. These situations include drill stabilization, helping to hold grocery bags, and extra climbing support.

SRLs encompass more than just arms. Kurek and Asada describe an SRL that is used to help with tasks low to the ground, supporting the operator's weight while crawling [9]. These are effectively supernumerary robotic legs. Hussain et al. designed a robotic sixth finger to help stroke patients grasp objects [10]. While the robot itself had a simple task, open or close to grip or release an object, it was directly controlled by the user with an EMG (Electromyography) cap.

This was most likely due to the difficulty with SRLs in determining the intent of the operator. Normally, an SRL must decide what the operator wants in order to provide assistance. It is significantly easier to directly control an SRL, than for an SRL to determine a person's intent. Thus, a foot-controlled SRL can avoid this complication while leaving the operator's hands free to perform tasks.

Some work has been conducted on foot-controlled SRLs. Wentzel et al. describe using the foot to send commands to a robot [3]. The robot could then be used to assist with soldering, a task that often is difficult with just two hands. Not much work on control of the robot with the foot is presented beyond the concept itself. Sasaki et al. presented a design for a foot-controlled robot arm [6]. The arm was operated using foot position, orientation, and toe curl. However, little detail is provided on performance with the arm or effectiveness of control.

Some tests have been conducted in virtual reality with extra arms. Abdi et al. had participants perform several tasks using two hands and a foot, which were recorded by an Xbox Kinect and displayed as three virtual hands. One such task is catching falling objects, which participants were able to perform better with three hands than two [11]. Another task is controlling a camera with the foot and a commercial foot-mouse in simulated laparoscopic surgery [12].

2.2 Foot Interfaces

Foot interfaces are not as common as hand interfaces. However, there has been research into using the foot instead of hand controls, primarily for human-computer interaction. Velloso et al. describe three categories of foot sensing methods; mediated, intrinsic, and extrinsic [13].

The first type of sensing method, mediated sensing, involves the leg manipulating a physical device. The most common use of mediated sensing is a pedal, such as is used when driving a car [13]. This method is also seen in some of the earliest computer interaction devices. English et al. included a simple knee device in a test of computer input devices in 1967 while developing the computer mouse [14]. They found that, among users inexperienced with either device, the mouse and knee control had similar speed performance. Now people are very familiar with the mouse, so more practice may be necessary for people to reach the same level of proficiency with the leg. Knee control did have a higher error rate and was more physically fatiguing [14]. Nineteen years later, Pearson and Weiser worked on methods to supplement computer use with foot controls to replace the mouse [15]. They proposed several designs for foot interfaces that used mediated sensing. One such design was a pendulum device. This device consisted of a foot plate hanging from a rope attached at the point of rotation. Moving the plate rotated the top of the device and pushed an upside-down joystick in the direction of rotation, which is then interpreted as a directional command. Since then, more mediated sensing foot interfaces have been developed for various purposes. For example, Springer and Siebes presented a device in 1996 that used two feet to rotate a plate and control a computer mouse [16]. This interface was created as a computer aid for people with physical disabilities. This interface was slower than the hand mouse, and users indicated they would prefer a single-foot controller. In 2015, Klamka et al. combined the use of foot pedals and gaze to pan and zoom on maps, leaving the hands free to perform the actual selection [17].

The second sensing method, intrinsic sensing, uses sensors that are attached to the leg and feet to provide input [13]. One example of intrinsic sensing includes a pair of shoes containing pressure sensors and accelerometers. These shoes were created to capture motion for use in interactive dance and gestures [18]. Another example is the control scheme for the DEKA prosthetic arm. Here the operator wears force sensitive resistors that are used to manipulate the arm [19]. Because the sensors are attached to the foot to track the toes, the interface created by Sasaki et al. includes an example of intrinsic sensing [6]. This interface, also involves extrinsic sensing.

For the third method of sensing, extrinsic sensing, environmental instruments record the motion of the legs and feet [13]. This includes the foot tracking presented by Sasaki et al. [6]. In 2015, Gunawardena and Hirakawa presented an extrinsic sensing interface capable of classifying gestures of the foot via a water tank filled with an array of break-beam sensors [20]. Wentzel et al. and Abdi et al. describe using extrinsic sensing of the foot by using a Microsoft Kinect to track motions of the foot [3, 11].

While each of the three sensing methods have advantages and disadvantages, this thesis will focus on mediated sensing as it is safer for robot control, less noisy, less fatiguing, and provides a measure of feedback to the user. Operators of a foot interface using this method can easily stop interacting with the interface without removing the interface or leaving the area. This decreases the possibility of accidental input. The user of such an interface also receives passive haptic feedback from the device during operation [13]. The physical interface also provides support to the operator, reducing fatigue, because the operator may rest their foot on the device while using it instead of holding the foot in the air. The sensors used in mediated sensing are typically less noisy than vision systems common in extrinsic sensing. This is because vision based systems have to deal with more environmental noise, while physical sensors do not.

2.3 Interface Control Methods

Although many foot interfaces have been developed, little work has been done on how to best use them for control. For hand interfaces, it has been shown that position control tends to have better performance than rate control when moving to a target location [21]. Rate control has an advantage when the workspace is very large, or when system dynamics require slow movements [21]. The difference between these control methods is not as well recorded for the foot. An experiment by Kim and Kaber tested the difference between the two control methods for the foot. This was done using two pedals to select the desired size of text in a computer document. They found that rate control was more accurate and easier to use for their application [22]. This was done in only one degree of freedom, with gas and brake pedals, which is often used in a rate control setting in cars. Since SRLs are not very useful in just a single degree of freedom, testing should be done in more degrees of freedom.

Regardless of the control method used, it is important to determine the overall effectiveness of any foot interface. The hand provides a commonly used benchmark. Pakkanen and Raisamo compared the ability of the hand and the foot to perform spatial tasks using a trackball [23]. They found that, while slower, control using the foot can be reasonably accurate. In another study by Pearson and Weiser attempting to compare the use of a planar foot interface to a standard computer mouse, they found that the hand mouse outperformed the foot interface [24]. Garcia and Vu also sought to compare the ability of a user to operate a foot mouse to a hand trackball [25]. Due to the lack of experience most people have with foot interfaces compared to hand interfaces, this comparison was made both before and after practice. Garcia et al. found that the ability of a user to operate a foot mouse increased significantly with practice. Thus, the foot not be able to perform as well as the hand when teleoperating a robot arm, but this may be due to lack of practice. This is also supported by work conducted by English et al., which showed that people inexperienced using a computer mouse were just as effective with knee control as they were with the mouse [14].

2.4 Foot-Hand Coordination

The benefit of SRLs is the ability to perform a task using three limbs at the same time. Thus, it is crucial for foot-controlled SRLs that the operator is able to use both hands and foot control at the same time. Some work has been done on the simultaneous use of both hands and a foot. Abdi et al. showed that participants were capable of operating both hands and foot to perform a coordinated task, catching falling blocks in virtual reality. They also found that participants could move all three limbs simultaneously with intent [11]. Since just having the extra arm may cause an improved likelihood of catching blocks, more work needs to be done regarding coordination of the hands and a foot.

Klamka et al. showed that participants were able to use foot control, gaze control, and the hands to pan, zoom, and select points on a map [17]. Participants in an experiment by Abdi et al. were required to move one hand and the foot at the same time, then both hands and the foot at the same time [12]. The foot was used to control a camera, and the hands were used to control surgical grippers in virtual reality mimicking laparoscopic surgery. This was only done with single-handed and two-handed tasks, making no comparison between two hands with one foot and just two hands. This thesis makes the comparison between two hands with one foot and just two hands, using an SRL to accomplish a challenging task.

3. FIRST INTERFACE AND EXPERIMENT

The difference between rate and position control for the foot is important for foot-controlled SRLs. A foot interface is designed to test these two control methods using 2D reaching tasks. Use of this interface is also compared to the hand. Performance with the interface was poor, so the experiment was stopped prematurely, however, the data that was collected provided useful criteria for a second iteration.

3.1 Foot Joystick

The first interface, the foot joystick, is shown in ***Figure 3.1***, was created from an existing hand joystick, fitted with a metal plate on top. All buttons and attachments were removed from the handle of the joystick to make room for the plate. Initial testing shows that rotation of the ankle while attempting to apply force can increase discomfort while using the interface. Thus, a universal joint was added to allow the plate to move in any direction and stay level. A spring keeps the plate from tilting due to gravity. This keeps users from needing to roll their ankle while pushing around the joystick, and allows the plate to return to a horizontal position when released. A simple schematic of the foot joystick is shown in ***Figure 3.2***.

Figure 3.1: The foot joystick stands straight up when in the home position. The metal plate on top provides the point of contact between the device and the operator's foot.

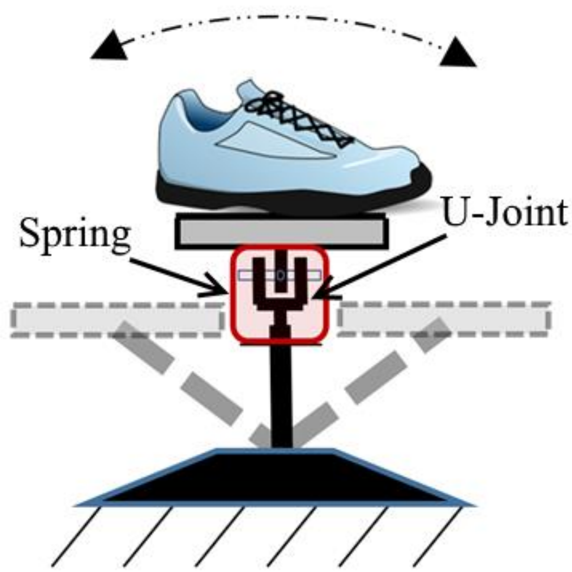

Figure 3.2: A schematic of the foot joystick shows the motion of the device. The dashed lines represent potential positions of the joystick. The plate on top is able to remain flat throughout movement because of the universal joint. The location of the spring and universal joint are represented by a red box.

The spring return of the joystick, unmodified, is enough to return the plate to an upright (zero) position when pressure from the leg is released. This is ideal for rate control, where the interface must return to the center to stop movement. The spring return could not be reasonably removed for position control because it made it very difficult for the user to feel the position of the interface. The foot interface would also fall to the side without the spring return if not held in place by the user. This would make using the interface exceptionally difficult.

3.2 Experiment

The purpose of this experiment was to compare position and rate control using the foot interface. The comparison is also made between the foot interface and a standard hand interface. Participants completed a two-dimensional positioning task using both methods. Participants were told to try to move to target positions as quickly as possible. This task is simple for novice users, allowing them to quickly learn the task and optimize their performance. This helps lower the effect of learning the task itself. Their performance was evaluated by measuring time spent traveling between positions, normalized by the distance required to reach them all.

The task each time was identical. Images of the task are shown in ***Figure 3.3*** and ***Figure 3.4***. The participant's goal was to move a red, circular marker into a yellow, square target location. Entering the yellow square caused the marker to turn green, letting the participant know they were inside the target. After holding the marker inside the target location for a full second, a white circle appeared to preview the next target location. To prevent the participant from anticipating the movement of the yellow square, a random delay between 0.5 and 1.5 seconds determined how long the participant must stay in the yellow square with the white circle on display. Leaving the yellow square prematurely caused the white circle to disappear and the timer to reset. After the delay, the yellow square disappeared from the old location and reappeared at a new location, replacing the white dot.

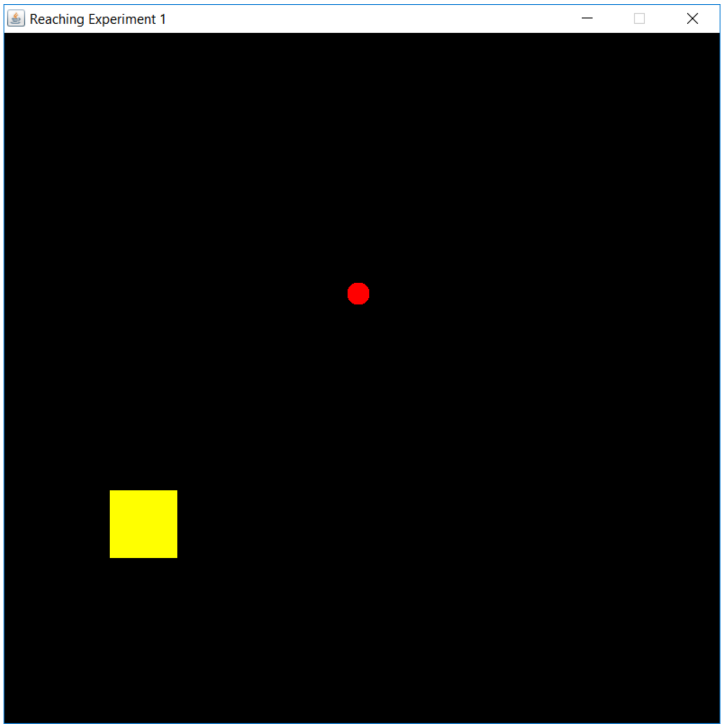

Figure 3.3: The marker controlled by the participant is red while not inside the target, the yellow square.

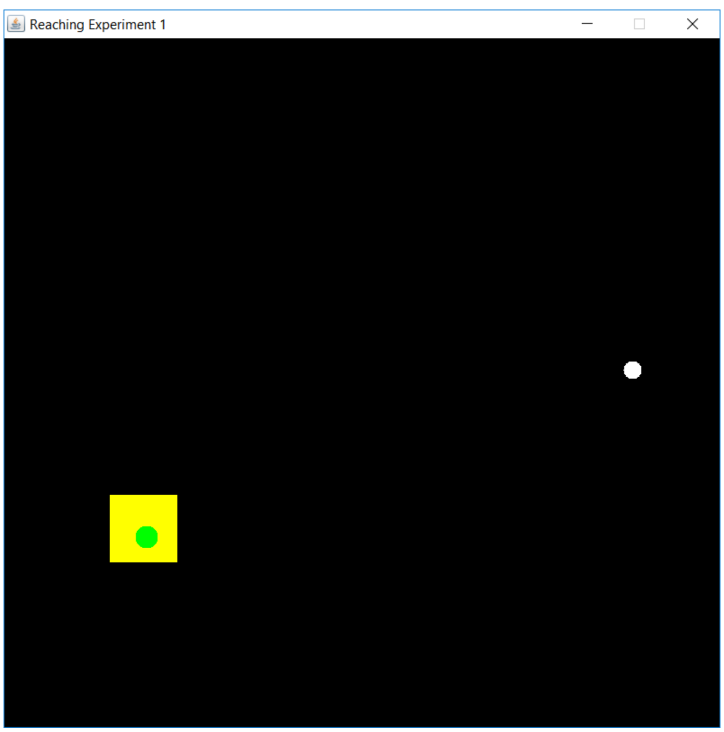

Figure 3.4: The marker is green when inside the target space, and a white preview dot appears at the next target location prior to the target location moving.

The first location is the center of the window, and travel time begins recording once the participant reaches this location (staying inside until it moves). Each new location is randomly selected from all non-visited locations that make up a circle of eight points. This random order of locations was calculated separately for each participant. Once all of the locations have been reached, the target returns to the center and the test is concluded after the final target is reached. All time spent with the cursor outside the target location is counted towards travel time.

Eight participants were recruited from the student population of Rose-Hulman Institute of Technology. Before beginning, each participant was asked for demographic information regarding age, videogame and sports participation, and dominant hand/foot. This information is recorded in Appendix A. Each participant was asked to complete the positioning tasks with two different control methods, rate and position, and two different interfaces, hand and foot. The four combinations of control method and interface were: rate-hand (RH), position-hand (PH), rate-foot (RF), and position-foot (PF). To minimize ordering effects, a Latin square design was used to split the participants into four groups, as is shown in ***Table 3.1***. The participants completed the tasks in the order described by the group they were assigned.

Table 3.1: Test groups used to prevent ordering effects.

Group 1	RF, PF, RH, PH
Group 2	PF, PH, RF, RH
Group 3	PH, RH, PF, RF
Group 4	RH, RF, PH, PF

For each task, the participant used his or her dominant foot or hand to operate the interface, and control the output marker on the screen. For position control, the location of the input interface directly correlated to the marker’s position. For rate control, the location of the input interface determined the direction and speed of movement of the marker. The foot interface was the same for both position and rate control. Similar to the foot joystick, the hand joystick had all the extra buttons removed from the handle. The spring return remained in the hand joystick regardless of the control method used. This also matched the foot joystick. The modified hand joystick is shown in ***Figure 3.5***.

Figure 3.5: The hand joystick for the first experiment had all buttons removed from the handle. The spring return keeps the handle in an upright position when pressure on the handle is released.

Before starting each test, the participant was given the opportunity to familiarize themselves with the control. Once the participant completed the final target location, the test automatically concluded. At this point, the participant filled out a modified NASA Task Load Index (TLX) survey. This involved rating the mental, physical, temporal demand, perceived performance, required effort, and level of frustration for the previous test. This rating was completed by marking a scale from low to high. The survey is included in Appendix B.

After completing all four tests, the participant was asked to return after at least two days to repeat the tests. The two day break is short enough to allow recollection of the task and control methods, while still permitting adequate resting time. Upon returning, the participant performed the same tests as before, in the same order. This is done to determine the effect of practice on test performance.

3.3 Statistical Methods

The Wilcoxon signed-rank t-test is used to test for statistical significance in data that does not fit a normal distribution. One way to test for a normal distribution is to use the Kolmogorov-Smirnov test. The Wilcoxon test requires data to be paired, e.g., patient data collected before and after medication. The first step is to calculate the difference in each pair of data, then rank these differences from lowest to highest absolute value, removing any values that equal zero. The rank, R_i, is calculated as

$$R_i = rank\left(\left|x_{2,i} - x_{1,i}\right|\right),$$

where $x_{1,i}$ and $x_{2,i}$ are the paired data points. The test statistic W is calculated by

$$W = \sum_{i=1}^{N_r} sgn(\,x_{2,i} - x_{1,i}) * R_i,$$

where N_r is the number of differences that are larger than zero. N_r is also used to calculate the standard deviation σ_W,

$$\sigma_W = \sqrt{\frac{N_r(N_r + 1)(2N_r + 1)}{6}}.$$

Finally, a z-score can be calculated as

$$z = \frac{W}{\sigma_W}.$$

The z-score can then be used with a z-table to calculate the *p* value for the test. The lower the *p* value, the less likely the difference between the values was due to random variation.

When making multiple comparisons, the probability of getting a false positive increases because there are more opportunities for the error to occur. Thus, a Bonferroni correction can be used. This is done by dividing the alpha value, $\alpha_{critical}$, by the number of comparisons being made, $N_{comparisons}$, as seen in the equation

$$\alpha_{corrected} = \alpha_{critical}/N_{comparisons}$$

The new alpha-value is compared to the *p* value to determine statistical significance. If the *p* value is lower, then it is statistically significant to the degree of the critical value. This test is conservative in that the likelihood of falsely finding results to not be significant is raised. The purpose of the test is to decrease the likelihood of reporting results to be significant when they are not.

3.4 Results and Discussion

For each target location in a trial, the time the participant took to reach the target is divided by the minimum distance (in pixels) required to get there. This was done to prevent short movements from having an undue advantage over longer movements. Bar plots for average time normalized by distance are shown in **Figure 3.6**. Only results from the first trial are included, since only four of the eight participants returned for the second trial.

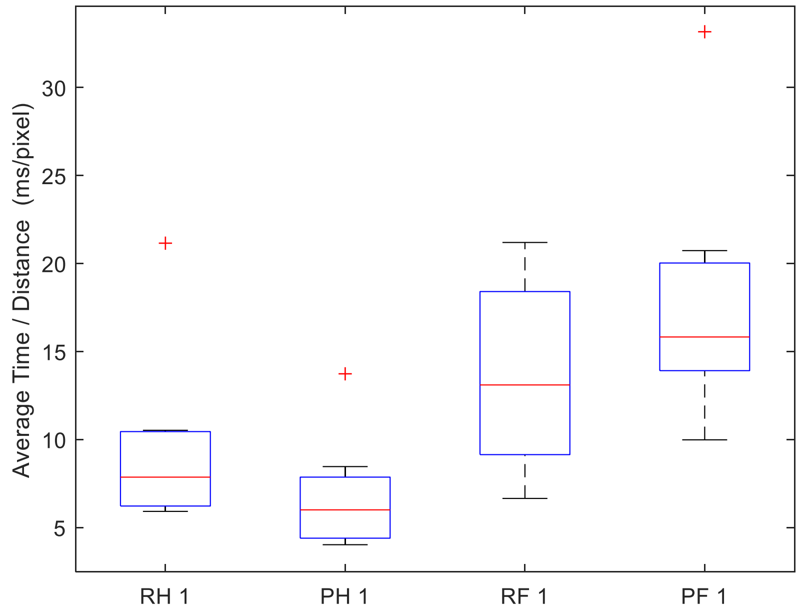

Figure 3.6: Average travel time normalized by distance for each combination of interface and control method, Rate Hand (RH), Rate Foot (RF), Position Hand (PH), and Position Foot (PF) is shown. All data is from the first trial. A lower score is better. The red center mark represents median, with boxes marking 25th and 75th percentiles. Whiskers are min and max, non-outliers.

Data from one participant was removed from the analysis. This participant attempted the task while wearing heavy, steel-toed boots, and the resulting PF data does not fit reasonably on the above plot, as it is above 55 ms/pixel. All other outliers shown in ***Figure 3.6*** are included in the analysis. The Wilcoxon signed-rank test with a Bonferroni adjustment for multiple comparisons was used to determine statistical significance of the results. For this foot interface, rate control appears to perform better than position control. However, none of the differences between tests were statistically significant. The *p* values for each comparison are shown in ***Table 3.2***.

Table 3.2: *p* values for normalized travel time data from experiment 1 show that no results are significant.

	p value
RH1 ≠ RF1	0.078
RH1 ≠ PH1	0.016
RH1 ≠ PF1	0.016
PH1 ≠ RF1	0.016
PH1 ≠ PF1	0.078
RF1 ≠ PF1	0.016

Comments from participants indicated that they found the foot interface very difficult to use. Specifically, the interface required participants to keep their leg raised in order to prevent the weight of their leg from inadvertently moving the joystick. This was a source of fatigue, and was made worse if the participant wore heavy shoes.

In addition to being fatiguing, control of the foot interface was difficult to maintain. Specifically, participants had difficulty in moving across the center point of the foot joystick. This was likely due to the fact that the center point of the interface was an unstable equilibrium point and any pressure placed on the foot joystick was likely to push the plate in an unplanned direction. Since the foot plate was a fixed distance from the center of the joystick, the plate followed an arc about the point of rotation as can be seen in ***Figure 3.2***. This arc curved the opposite direction as the natural motion of the leg, forcing users to move in a non-intuitive way. This would affect position control more than rate control with the foot, because position control had to maintain the unstable point for a longer period of time. This made this device less useful for control.

The perceived difficulty of using the foot interface is shown in the modified NASA TLX survey data displayed in ***Figure 3.7***. The foot interface was reported to be more demanding than the hand interface. Performance with the foot interface was also rated poorly. No performance differences were noted due to demographic variations.

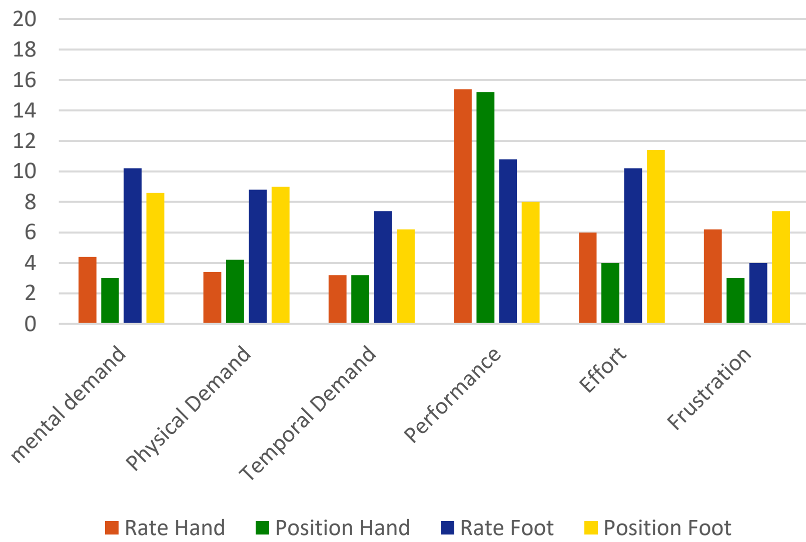

Figure 3.7: Experiment 1, trial 1 modified NASA TLX results are better for the hand than the foot. Scores are rated from low (zero) to high (twenty) with a neutral score of ten. A lower score is better for all metrics except performance.

Due to difficulty of use and dissatisfaction with the interface, it was determined that this interface was not a good candidate for controlling a SRL. Thus, the experiment was abandoned prematurely. The comparison between rate and position control was not valid for this experiment because the interface was not good enough to provide a legitimate comparison. Furthermore, for both the foot and the hand, position control was tested with an interface that contained a spring return. This is contrary to common practice, and will negatively affect position control because the interface is constantly trying to move to center.

A second foot interface was designed to solve the issues exposed by this experiment. Issues with the experimental procedure were also addressed, and are described in the next section.

4. SECOND INTERFACE AND EXPERIMENT

Due to issues with the previous interface and experiment, a second experiment was run with a new interface to compare position and rate control with the foot. The second iteration of the foot interface is a planar device. This new design is intended to correct many of the issues that caused poor performance in the previous interface. The interface was tested using both position and rate control, and compared to the hand using the same control methods.

4.1 Planar Interface

As seen in the previous device, raising and lowering of the leg can be undesirable when controlling an interface, due to both inaccuracy and fatigue. A new interface was needed to avoid this motion of raising and lowering the leg. Thus, a planar foot interface, shown in ***Figure 4.1***, was created. This interface allows the user to provide input while moving only in the horizontal plane. This fixes the vertical arc issue seen in the previous interface. This also allows the user to place weight on the interface while still being able to control the position of the interface. Since the motion is already familiar, little time is required to explain how to use the interface. The interface may also be easily adapted for both position and rate control.

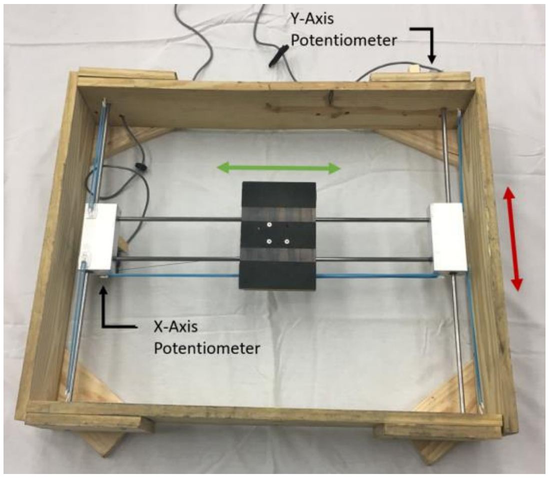

Figure 4.1: The planar foot interface allows motion in the horizontal plane. Green arrows show the direction of motion in the x-axis, and red arrows show the direction of motion in the y-axis. The user's foot rests on the black plate in the middle. String potentiometers labeled in the figure track motion of each slider.

The planar foot interface utilizes two sets of rails, and bearings/bushings to allow for smooth sliding. Both sliders have a maximum range of 15 inches. This size allows most operators to utilize their full range of leg motion when using the interface. If an operator is not able to reach the limits of the interface, a simple barrier may be used to reduce the active workspace. Thus, with simple recalibration on the computer, the range of motion can be reduced without affecting the range of motion of the output.

The interface uses mediated sensing. Two string potentiometers provide an output signal based on the position of the sliding plate. The design of this foot interface is similar to that developed by Pearson, without the requirement of clutching or clicking [24]. This adjustment is related to the difference in purpose; the Pearson interface is intended to be used as a computer mouse, where the ability to click and to move the interface without providing input is important. The current device is intended ultimately to provide continuous control to a supernumerary robot arm. The functionality is also similar to Abdi et al. who created a similar planar foot interface for use with a robot arm [26]. Their interface included more degrees of freedom, but was not tested beyond the ability to be used for a single movement task.

The planar foot interface can be used for position control without any modifications. For rate control, large rubber bands are attached to provide the 'spring return' function. Thus, the user can release pressure on the interface, and the plate will return to the central location. Centering the interface stops all motion, and pushing towards the limits of the interface will reach a speed saturation before hitting the interface boundaries. The optimal maximum speed was determined during pilot testing to be 25 pixels per update loop. The dead band for the interface was chosen to encompass the overshoot caused by releasing the foot pedal when at one of the positional extremities. This means the bounce caused by the spring return won't cause extra input. Occasionally the pedal would experience undershoot when returning to center due to friction. This was often less severe than overshoot, thus already inside the dead band region.

4.2 Experiment

The purpose of this experiment is the same as the previous experiment, to compare position and rate control with a foot interface. The comparison between the foot and hand is made again as well. The same two-dimensional positioning task is used with some modifications. The metrics for performance were the completion time and distance ratio. The distance ratio is calculated as the distance traveled divided by the minimum required distance.

This experiment was identical to the previous experiment except for the device operated and a few adjustments. Twelve participants were recruited from the Rose-Hulman Institute of Technology student population and demographic information was collected. This information is available in Appendix A. The starting location was again the center of the window. Images of the task are shown in ***Figure 3.3*** and ***Figure 3.4***. Instead of eight locations around a circle, each new location is one of four pre-determined distances from the current location, in a random direction. The random seeds used were the same for each participant. The previous experiment often required many perfectly vertical or horizontal movements. It also was possible for a participant to only be required to make short movements following the circle. This new design ensures that short, long, and intermediate movements are required in a variety of directions. These locations were the same for each participant (each participant was required to move each of these distances an equal number of times to complete the task). Twenty targets, not including the starting location, made up a single task.

The participant was asked to reach each target as quickly as possible. The amount of time traveling to each target location was recorded as well as the distance traveled between each target. When a participant kept the cursor inside the target location for a full second (long enough for the preview circle to appear), the target is considered reached. Any movement after this, before the target moves to the new location, is not counted against the participant. This was changed to make sure that leaving a location early to try to get to the next location was not treated the same as overshooting the target.

Before each test, participants are given a full minute to practice with the interface. After reaching all the target locations, they rest for another minute before repeating the task with the same interface and control method for a total of 40 targets reached. This was different than the previous experiment. Several times during the previous experiment, participants appeared to not fully understand the task until it was nearly completed.

For this experiment, the same foot interface is used for both position and rate control, with the rubber bands added for rate control. For hand input, separate joysticks are used depending on the control method involved. For position control, the hand interface is modified to remove the spring return. This is a necessary condition for position control that was not addressed in the previous experiment. Some external parts of the handle were also removed because they imbalanced the joystick, causing gravity to effect the position asymmetrically. The same model of hand joystick is used for rate control without any modification. The rate joystick uses the same maximum speed and proportional dead band as the foot interface. The joystick for position control is the same as ***Figure 3.1*** with the spring removed. The joystick used for rate control is displayed in ***Figure 4.2***.

Figure 4.2: The hand joystick, unmodified, was used as a rate control device in experiment 2.

4.3 Results and Discussion

Column plots for average time and distance ratio are shown in **Figure 4.3** and **Figure 4.4** respectively. The average time represents the total time between each target to complete a task, averaged over the set of users. The average distance ratio is the ratio between the total distance traveled to complete a task and the optimal, straight-line distance, averaged over the set of users.

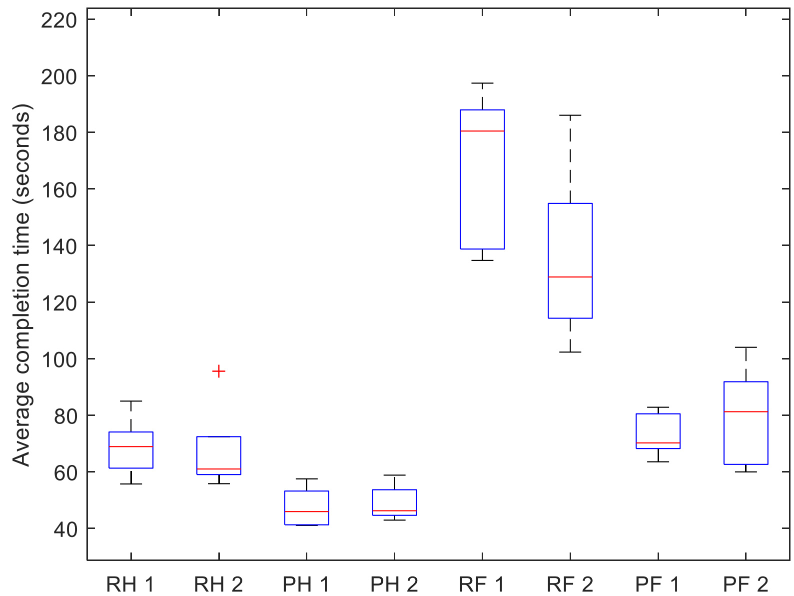

Figure 4.3: Average completion time for the second experiment is based on the time in-between reaching target locations. Each combination of control method and interface are included. Results are split between trial 1 and trial 2. The red center mark represents median, with boxes marking 25^{th} and 75^{th} percentiles. Whiskers are min and max, non-outliers.

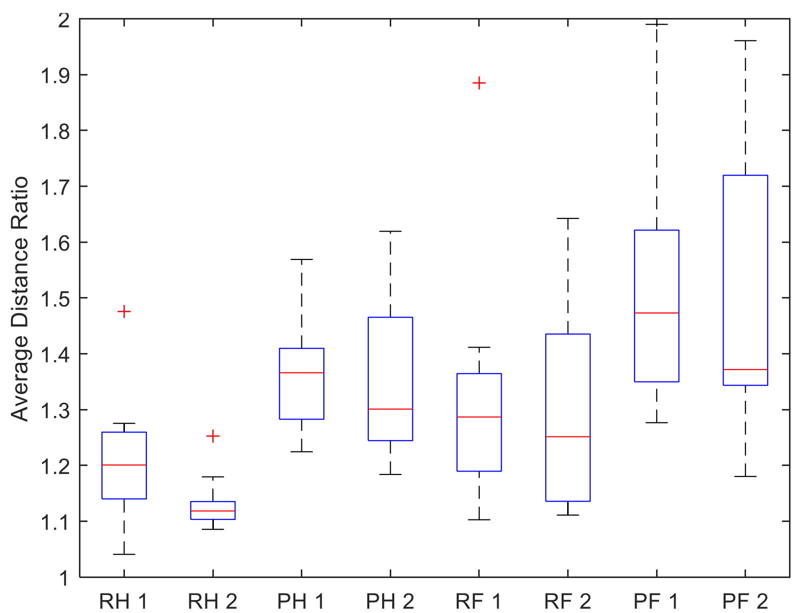

Figure 4.4: Average distance ratio for the second experiment is calculated by dividing the total distance traveled with the optimal distance. Each combination of control method and interface are included. Results are split between trial 1 and trial 2. A distance ratio of 1 indicates a perfectly straight line between target locations, and is the minimum value possible. The red center mark represents median, with boxes marking 25^{th} and 75^{th} percentiles. Whiskers are min and max, non-outliers.

The two-sided Wilcoxon signed-rank test was used to determine statistical significance because the data does not follow a normal distribution. This was determined by using the Kolmogorov-Smirnov test. A Bonferroni adjustment was made for the multiple comparisons. Since the differences between the first and second trials are relatively small, only the comparisons of the second trial are presented. The results are the same when comparing data from the first trial. The p values for comparisons between each control method and device are included in **Table 4.1**. Outliers shown in the box plots were included in the statistical analysis.

Table 4.1: *p* values for the comparison between each device and control method in experiment 2 shows significant differences. Values less than 0.0083 (bolded) indicate a significant difference at a 95% confidence. Most time comparisons are significantly different at 99% confidence with values less than 0.0017. Alpha values include the Bonferroni correction.

	Completion Time	Distance Ratio
RH2 ≠ PH2	**0.0015**	**0.00098**
RH2 ≠ RF2	**0.00048**	**0.00049**
RH2 ≠ PF2	**0.0024**	**0.00049**
PH2 ≠ RF2	**0.00048**	0.424
PH2 ≠ PF2	**0.00048**	0.077
RF2 ≠ PF2	**0.00097**	0.0093

For completion time, position control was significantly faster with the hand, matching previous research by Kim [21]. The foot yielded similar results, with position control completing tasks significantly faster than rate control. This suggests that the hand and foot operate similarly with regards to control.

Completion time for the hand was significantly faster for both control methods than for the foot, with most comparisons meeting a 99% confidence interval. The difference between RH and PF only satisfied a 95% confidence interval. This is because a few people performed better with PF than RH, while most did not.

There is a significant difference between the distance ratios for the two control methods with the hand, but not the foot. Trajectories for each interface and control method show that position control paths are very "noisy". This noise causes the marker to move more, increasing the distance ratio. The noise is particularly noticeable closer to the goal location where the operator must bring the device to a stop and hold it still. Rate control, however, has smooth paths towards the target, and is steadier once stopped.

Another reason position control had a higher distance ratio is the objective of the participant during the experiment. Participants were told to move to the targets quickly and were not attempting to optimize distance. If participants were told to optimize distance, they would have to slow down in order to monitor the path they were taking with position control. Since rate control already moved slower, it is both easier and more important to follow a shorter path. A set of trajectories for each interface and control method is shown in ***Figure 4.5***. The paths taken by participants from one target location to the next target location is shown.

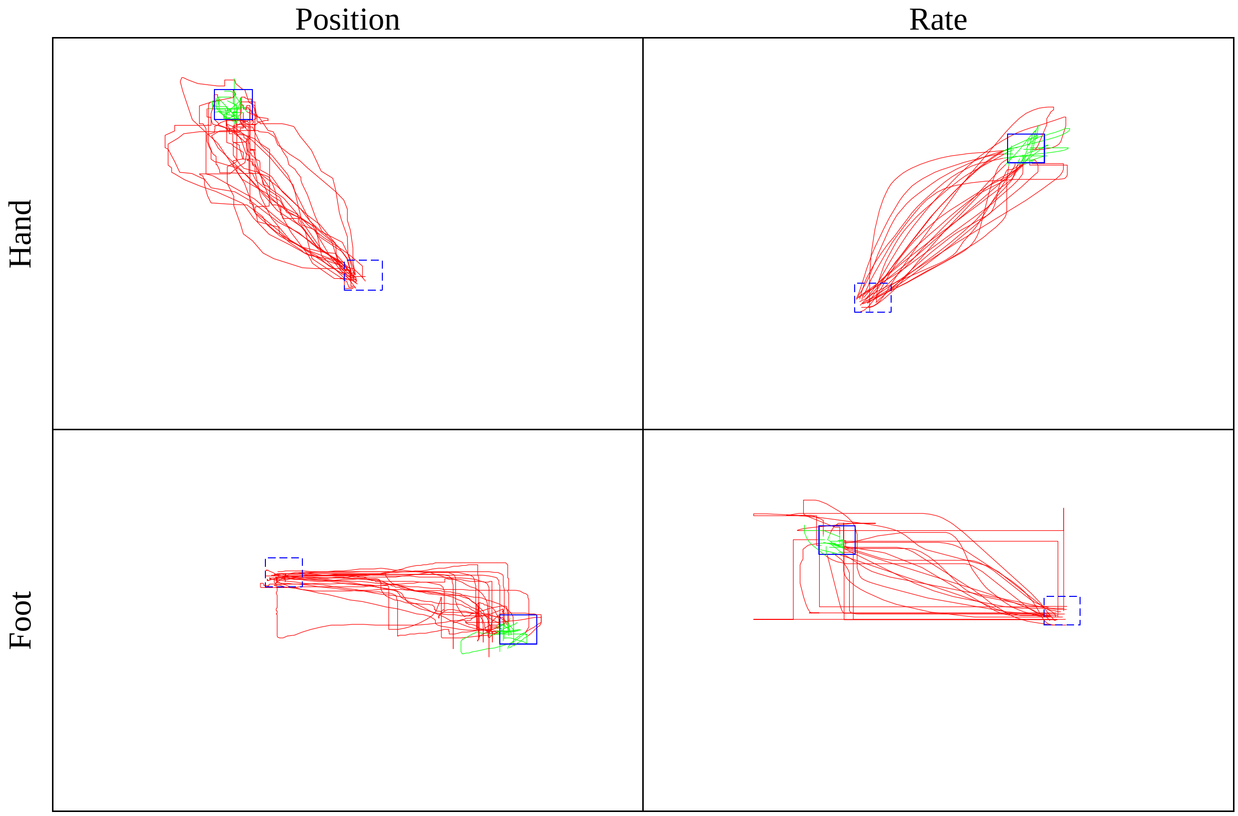

Figure 4.5: Trajectories from similar movements for each device and control method during the second trial show the path taken by each participant. Red lines represents the path taken by participants from the previous goal (dashed blue line) to the edge of the new goal (solid blue line). The green line is the path taken by participants after entering the target location for the first time and before the target is considered completed (occurs after one full second in the target location).

One observed strategy that can be seen in ***Figure 4.5*** among participants using foot control was to move along a single axis at a time to get to the target location. Many participants relied heavily on this strategy. This resulted in a longer distance travelled than moving diagonally towards the target. It is possible that users of this strategy found it easier to use simpler motions with the foot. Performance with the foot may be improved by using a better strategy.

Rate control was also easier to stop and hold still in the target location. **Figure *4.6*** shows the average distance traveled in pixels after entering the target location the first time until the target is completed (the cursor stays in the target location for a full second). This is also represented in **Figure *4.5*** by green lines. These results suggest that it is easier to hold inside the target location with rate control than position control.

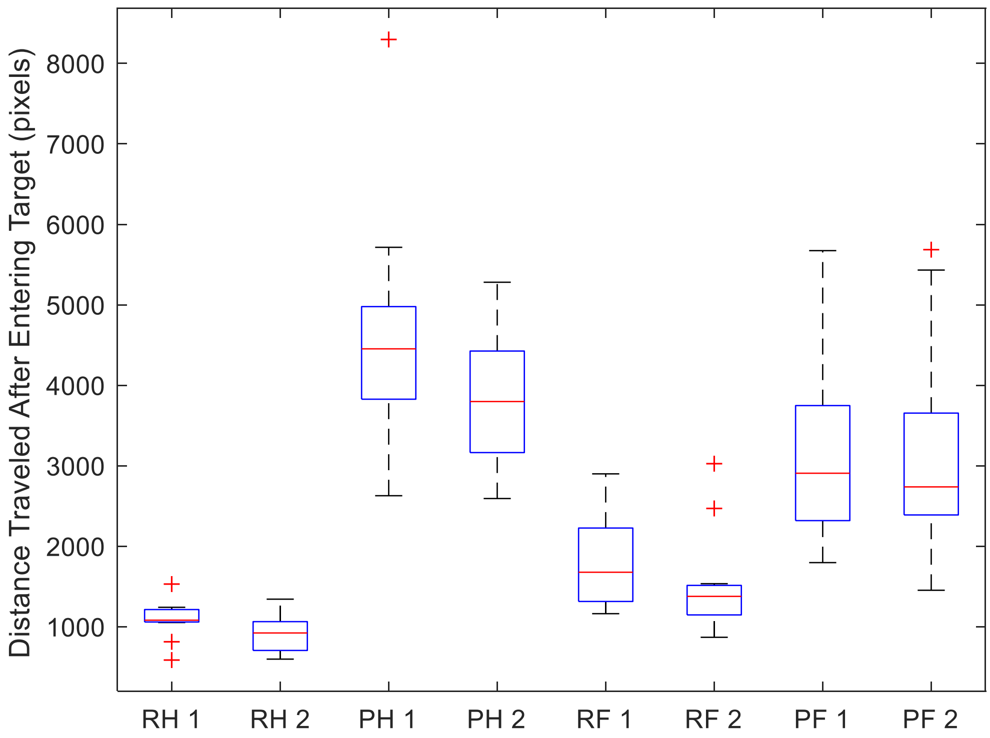

Figure 4.6: The distance traveled in pixels after entering the target location, before the target is completed, is higher for position control than rate control. The red center mark represents median, with boxes marking 25th and 75th percentiles. Whiskers are min and max, non-outliers.

Five participants were noted to use the single-axis control method significantly less than other participants. **Figure *4.7*** shows the distance ratios of just these participants. These ratios were much smaller for the foot than when combined with all subjects. This shows that it is possible to use the interface to move directly to the target, even though many participants chose to move one direction at a time.

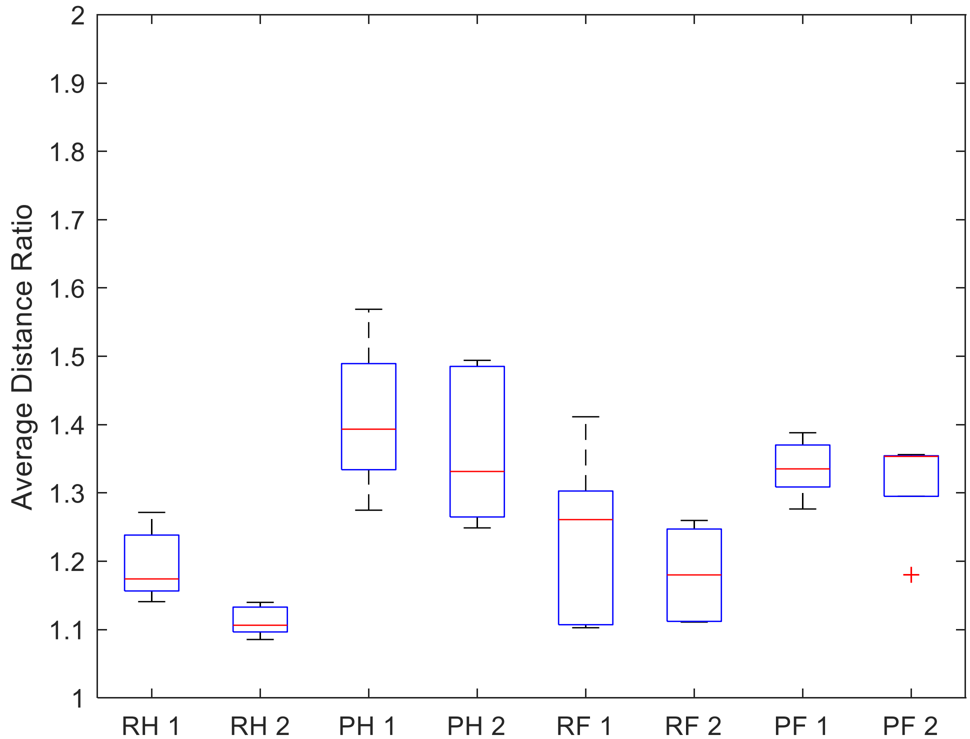

Figure 4.7: The average distance ratio of the foot is much smaller for participants who did not use the single-axis strategy. The red center mark represents median, with boxes marking 25th and 75th percentiles. Whiskers are min and max, non-outliers.

On the second day of testing, participants had more practice with the tasks. This practice was not a factor in performance. This may be because the amount of practice was not sufficient to cause a large effect. However, results for the foot had a larger standard deviation than for the hand. This indicates that the foot could improve.

The averages for the modified NASA TLX survey are shown in ***Figure 4.8*** and ***Figure 4.9***. The ratings from participants show that rate control was perceived to be more physically demanding than position control for both the hand and the foot. The foot interface was also rated to be more physically and temporally demanding than the hand interface. All interfaces and control methods showed a drop in reported effort between the first and second trials, indicating that practice was a factor in how participants perceived the task. Interestingly, participants rated their own performance fairly similarly across all interfaces and control methods, in direct contrast to actual performance. This highlights the difficulty in self-evaluation. No performance differences were associated with demographic variations.

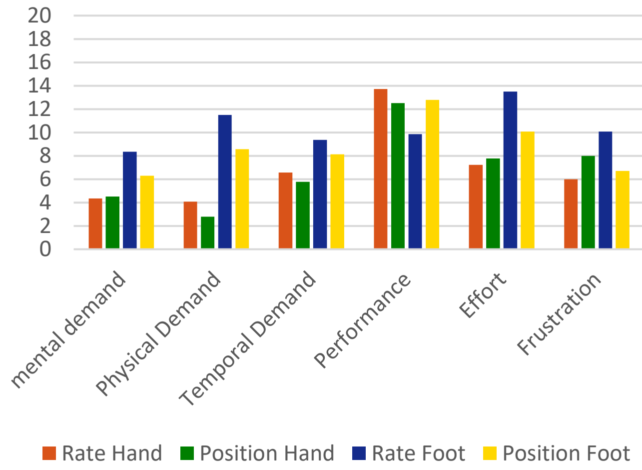

Figure 4.8: Experiment 2, trial 1 modified NASA TLX results are recorded. Scores are rated from low (zero) to high (twenty) with a neutral score of ten. A lower score is better for all metrics except performance.

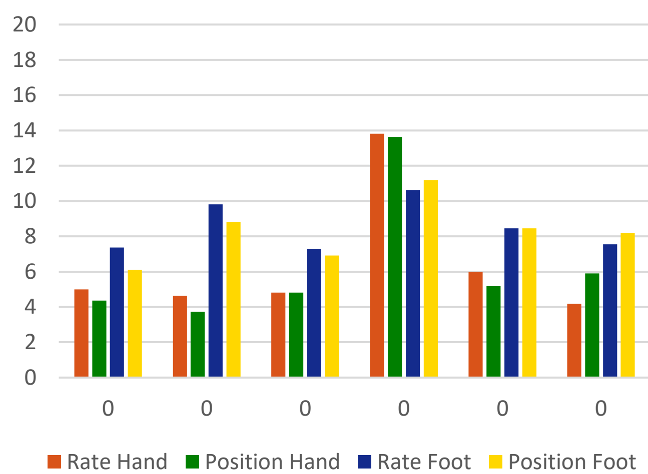

Figure 4.9: Experiment 2, trial 2 modified NASA TLX results are recorded. Scores are rated from low (zero) to high (twenty) with a neutral score of ten. A lower score is better for all metrics except performance.

The planar interface showed that position control is more effective than rate control with the foot. Position control was faster than rate control. At the same time, position control with the foot had the highest distance ratio because of a combination of poor strategy and noisy movements. As a result, position control covered more distance faster than other methods, since completion time was low. Position control with the hand and rate control with the foot had similar distance ratios. The first had more direct movements, but the path was noisy. The noise in position control was likely due to subjects' lack of effort in using an efficient path. However, taking a more efficient path would not make a large difference in time because the motion is very quick. Conversely, trying to force an efficient path would likely decrease the speed of motion. Rate control with the foot had smooth paths, but took an indirect route. Rate control with the hand was both direct and smooth, leading to a low distance ratio. Both foot control methods may have room for improvement based on the strategy used.

Position control with the foot was rated to be easier than rate control. Thus, it is reasonable that position control performs better than rate control because it is easier with the foot just as it is with the hand. Therefore, using this device to control an SRL would likely be most effective with position control.

5. SUPERNUMERARY ARM

In order to test the ability of a person to operate a foot-controlled SRL and use both hands at the same time, an experiment was conducted using the planar foot interface and a Sawyer robot from Rethink Robotics. The experiment requires performing a task with two hands and the foot interface. This is then compared to the same task using just two hands. The task itself was very difficult, and many participants performed poorly due to a lack of practice. To alleviate this, a new group of participants were given the same task after practicing for longer.

5.1 Experiment

The purpose of this experiment was to test the ability of a person to control an SRL while using both hands to complete a task. The task for this experiment was to navigate a marble tilt maze shown in ***Figure 5.1***. Typically, this requires the use of both hands to tilt the board along two axes in order to move the marble to the end of the maze.

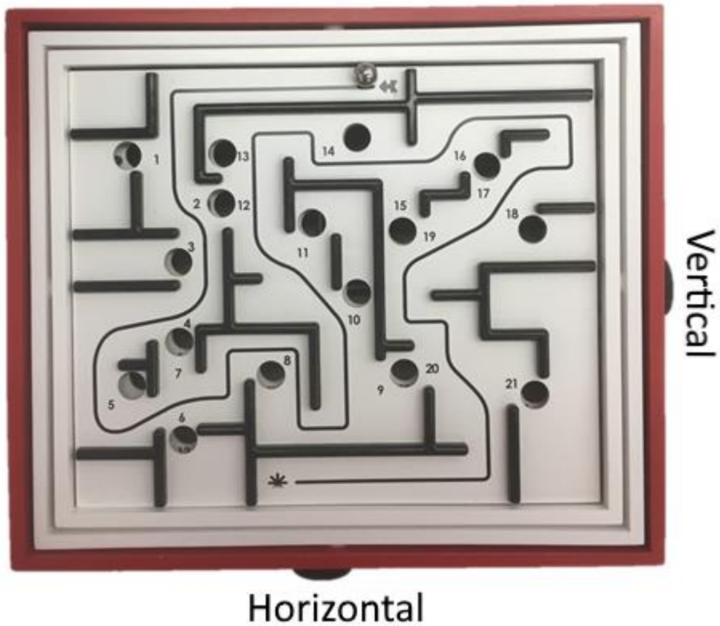

Figure 5.1: This Marble tilt maze was used in the experiment with the SRL. Turning the knob on the right tilted the board in the vertical direction. Turning the knob on the bottom tilted the board in the horizontal direction. The metal ball is next to the start location. The end of the maze is the star on the bottom.

In this experiment, the board itself was obstructed from the participant's vision. To compensate, the participant was given control of a robot outfitted with a camera. The camera only shows a portion of the board to the participant on a screen, and must be moved by the robot to provide vision throughout the maze. An example of what the camera shows is in ***Figure 5.2***. The participant is told to try to get as far as possible in the maze. Skipping over a hole (such as bouncing over hole 2 and landing in hole 13) is treated the same as falling into the hole that was skipped. This occurred several times.

Figure 5.2: The camera attached to the robot provided a limited view of the board. The ball is near hole 14, and must travel to the right to make positive progress.

Fifteen participants were recruited for this experiment. Before beginning, each participant was asked for demographic information including gender, age, hand/foot dominance, number of sports participated in, and if they were familiar with marble tilt mazes. This information is available in Appendix A. If the participant was not familiar with marble tilt mazes, extra care was taken to explain the game and demonstrate how it works.

Each participant attempted the maze three times under three different circumstances. The first set (three attempts) were unobstructed and without the use of the robot. This provided the participant with the opportunity to gain familiarity with the control of the board, and the task as a whole. The second and third sets (three attempts each) were obstructed. One set used the foot interface (***Figure 4.1***), and the other used the hand joystick (***Figure 4.2***) to control the robot. Half of the participants used the foot interface first, and half used the hand interface first. ***Figure 5.3*** shows the obstructed task with the foot interface, and ***Figure 5.4*** shows the obstructed task with the hand interface.

Figure 5.3: Foot control of the robot assists vision of the obstructed board. The participant must reach under the table to affect the board. Two hands are able to use the knobs, while the foot controls the camera. Only the computer screen is visible.

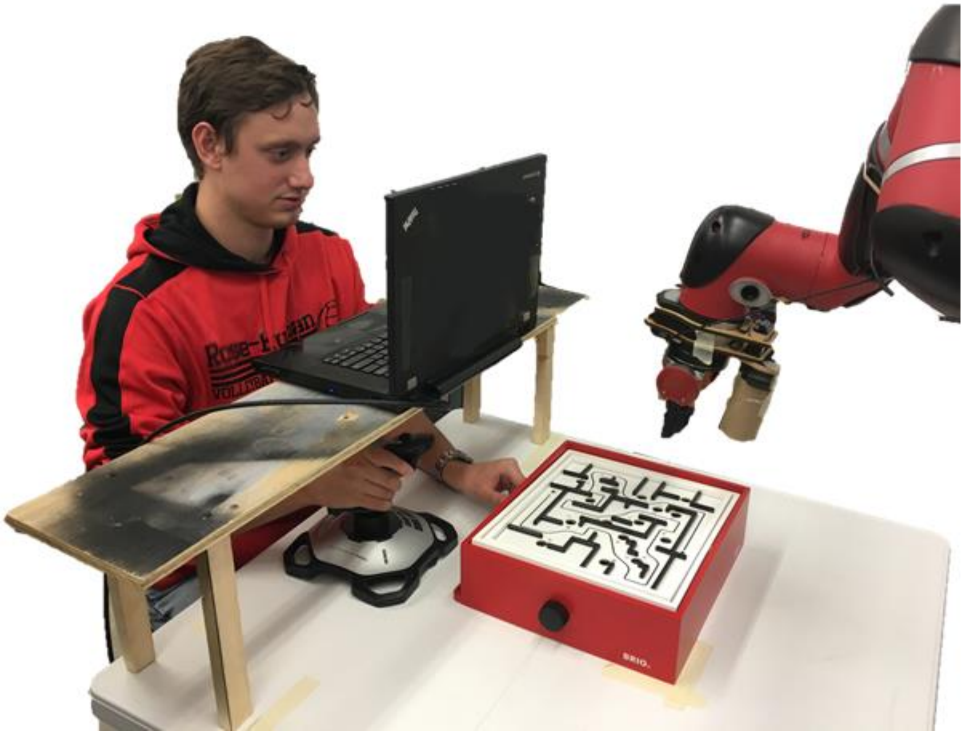

Figure 5.4: Hand control of the robot assists vision of the obstructed board. The participant must still reach under the table to affect the board. One hand must move between the camera control and one of the knobs. The hand joystick is allowed to be placed according to the operator's preference. Only the computer screen is visible.

When using the foot interface, the user may keep both hands on the tilt board while moving the robot to adjust the view. With the hand joystick, the participant must remove one hand from the board in order to move the camera. The time it takes to reach the end (or fall into a hole) was recorded as well as the number of the hole reached if the run was not successful in completing the maze. After the second set of attempts, the participant switched to the input interface not previously used, and repeated the test. Due to an oversight in protocol, only the last nine participants were asked to fill out a modified NASA TLX survey in-between sets of attempts.

5.2 Control

The Sawyer robot was teleoperated using either the planar foot interface for position control, or a hand joystick with rate control. The robot moved only in its x-y plane (horizontal).

The complete code required to control the robot is included in Appendix C. Position control was selected for the foot control as it provided the best results in the previous experiment. Rate control was selected for the hand control for several reasons. First, using position control for the hand requires constant contact with the joystick to maintain its position. This means that when the operator moved a hand from the interface to the maze knobs, the camera would move in an unpredictable direction. This would make the task impossible. Second, rate control with the hand performed more similarly to position control with the foot in the previous experiment. Therefore, we are able to test the ability of a person to perform the task using similarly performing devices.

5.3 Results and Discussion

The mean and median distance traveled (counted as the hole the participant fell in), maximum distance (furthest distance travelled per participant), and time taken are included in ***Figure 5.5***. If the participant reached the end of the maze, it was recorded as hole 22 because there are 21 holes.

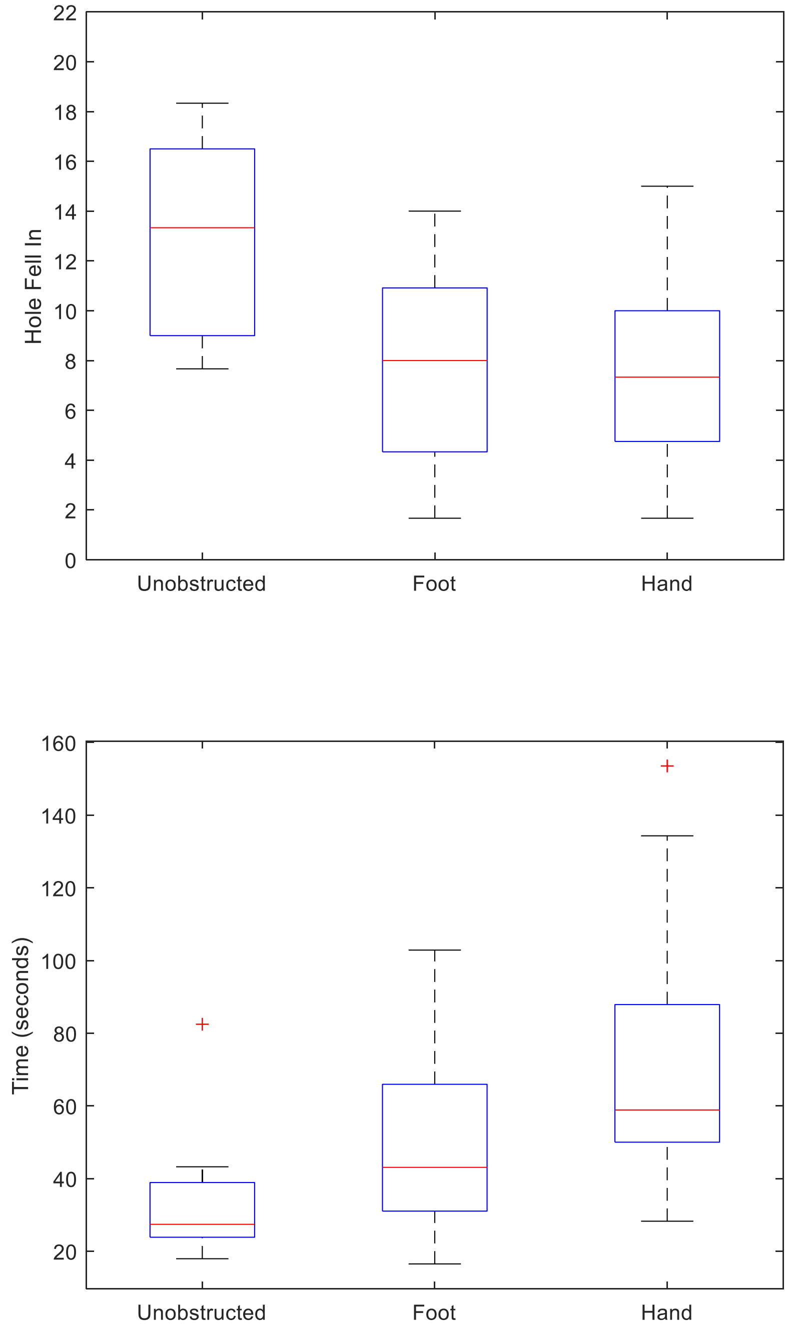

Figure 5.5: Box plots of each performance metric show similarities between the foot and the hand with regards to distance. Foot control is faster than hand control. The red center mark represents median, with boxes marking 25th and 75th percentiles. Whiskers are min and max, non-outliers.

The two-sided Wilcoxon signed-rank test was used to compare the foot and the hand for each of these three metrics as they are not normally distributed. Outliers shown in the box plots were included in the statistical analysis. The *p* values are included in ***Table 5.1***.

Table 5.1: *p* values for the comparison between foot and hand for each metric are used to test for significant difference. Distance traveled and max distance traveled are not significant, but time taken fits the 95% confidence threshold.

Distance Traveled	Max Distance Traveled	Time Taken
0.54	0.23	0.027

The hand and the foot performed very similarly for distance. This is likely in part due to the difficult nature of the task, as many participants had a difficult time making it past the first few holes. This is evidenced in ***Figure 5.6***, where the histogram of distance traveled is heavily weighted towards holes 1-4 for the obstructed trials. The task was difficult because the camera removed depth perception and added delay, and the robot moved slowly. Performance was much higher without these factors.

Figure 5.6: Histogram for distance traveled for all three trials shows that obstructed performance was poor compared to unobstructed.

The use of a single camera during the obstructed attempts makes the task significantly more difficult than the unobstructed attempt. Depth perception is reduced, so it is challenging to determine the tilt of the board. This means that the only way to determine the direction the ball will move is to wait for it to start moving.

Time delays also increased the difficulty of the task. A small time delay between the camera and the computer screen, and between the input interface and the robot made reacting quickly harder.

Another factor that increased the difficulty of the task was the slow speed of the robot. The max speed of the robot was relatively low compared to the max speed of the ball. This slow speed made keeping up with the ball more difficult as it sped up. This diminishes the advantage of foot control, because having a constant input to the camera while controlling the ball with the hands is still not enough to fully keep up. These extra challenges may in part be the reason so many participants fell in early holes.

While the hand and the foot were both able to make it the same distance through the maze, participants using the foot control were about 30% faster than the hand control. When using hand control, participants were forced to go slower, stopping the ball each time they wish to move the camera. This wasn't the case with the foot control, where it was possible to control the ball and move the camera at the same time. The ability to go faster is a clear advantage that foot control had over hand control. However, for this task, going faster may have led to more mistakes. Conversely, the slow nature of using the hand control may have led to a more cautious approach.

The last nine participants were asked to fill out modified NASA TLX surveys after each obstructed trial. Results were very similar for both and are shown in ***Figure 5.7***. This was very surprising as many participants indicated verbally that they preferred foot control. It is possible that the difference between the hand and foot was overwhelmed by the difficulty of the task. No differences were attributed to demographics.

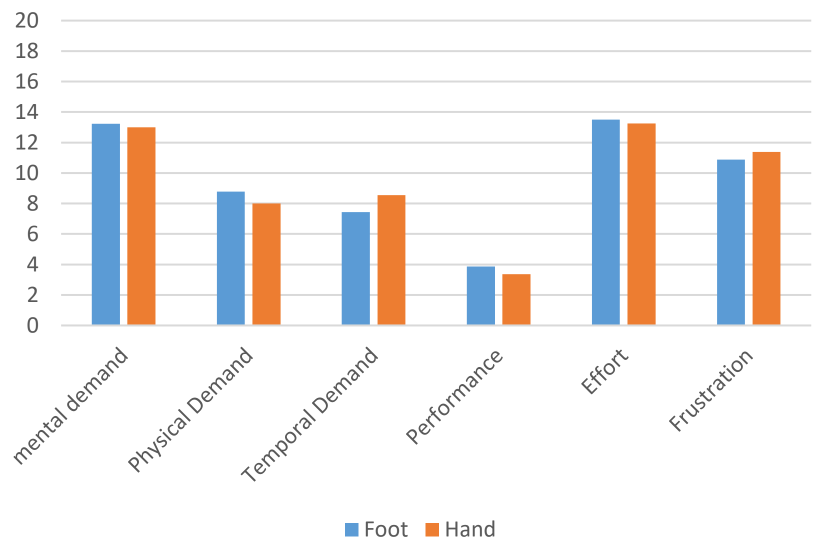

Figure 5.7: SRL experiment, modified NASA TLX results are recorded. Scores are rated from low (zero) to high (twenty) with a neutral score of ten. A lower score is better for all metrics except performance.

While many factors increased the difficulty of the task, one of the largest issues was a lack of practice. This is evidenced by the large number of participants that fell into the first two holes. To remedy this, more participants were asked to perform the same task, but given a more realistic amount of practice beforehand.

5.4 Practiced Results and Discussion

One downside for this experiment is that participants may need more practice to avoid falling to the first couple of holes due to inexperience. Thus, nine more participants were recruited. These participants were each given two minutes of unstructured practice time using the interface and tilt maze before recording the obstructed runs. This allowed them a chance to learn and compensate for lack of depth perception, vision and movement delay, and the slow speed of the robot. It also gave the participant the opportunity to develop camera movement strategies without fear of failure. The results of these nine participants are included in **Figure 5.8**, and a histogram is included in **Figure 5.9**.

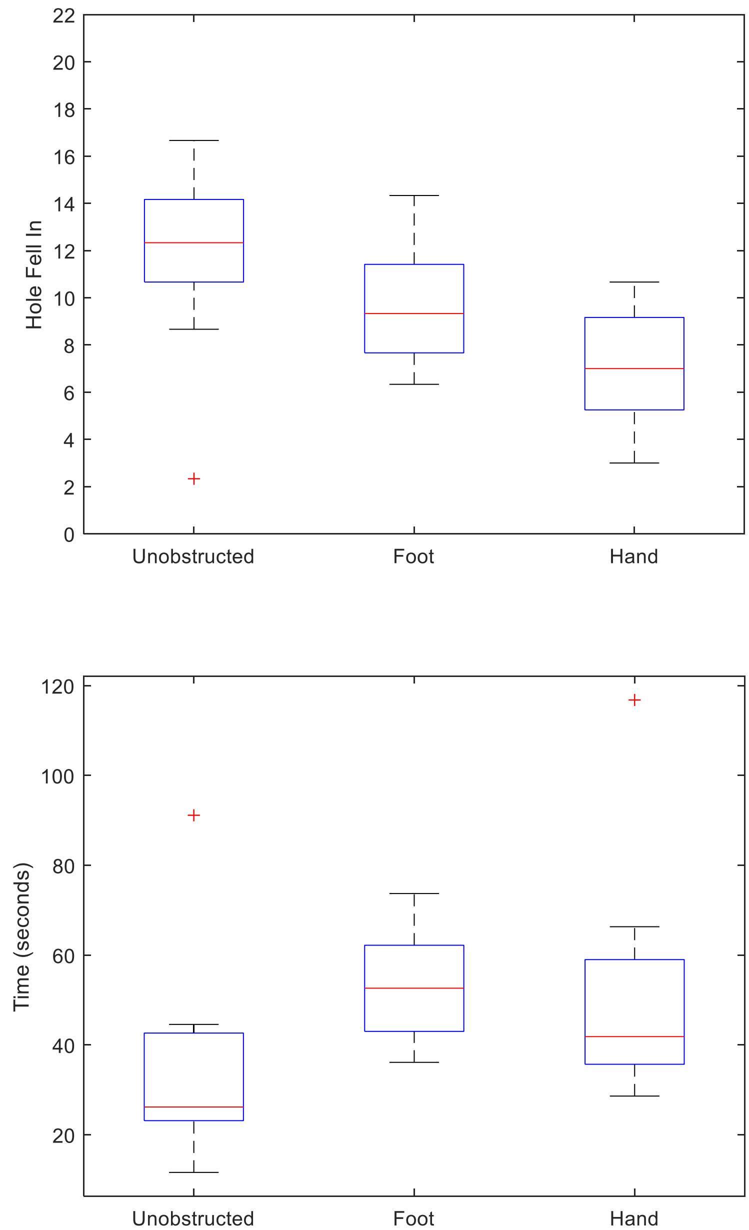

Figure 5.8: Bar plots of each performance metric show the foot is able to travel further than the hand. Hand control was slightly faster than foot control although, foot control traveled further. Raw values are included in Appendix D. The red center mark represents median, with boxes marking 25th and 75th percentiles. Whiskers are min and max, non-outliers.

Figure 5.9: Histogram data from practiced participants shows that the foot is capable of reaching much further than the hand.

The same statistical method was used to test this data. Outliers shown in the box plots were included in the statistical analysis. The *p* values are included in ***Table 5.2***.

Table 5.2: *p* values for the comparison between foot and hand of practiced participants test statistical significance for each metric. Distance traveled and time taken meet a 90% confidence interval.

Distance Traveled	Max Distance Traveled	Time Taken
0.071	0.15	0.01

With practice, participants went further when using foot control than when using hand control. Hand control appears to take less time than foot control, but this comparison cannot be truly made because the distances traveled are not similar. It naturally should take longer to travel a further distance, so it is reasonable for foot control to have taken more time than hand control. If you normalize the time taken by the distance traveled, foot control takes 5.9 seconds/hole on average while hand control takes 8.0 seconds/hole. Thus, the foot was faster than the hand. Both of these values were lower for practiced participants than those with less practice. The time per hole averages for the previous experiment were 6.8 seconds/hole for the foot and 9.8 seconds/hole for the hand.

Each of these participants filled out modified NASA TLX surveys after each obstructed trial. Results are included in ***Figure 5.10*** and show that these participants found foot control to be more physically demanding, but less mentally demanding and less frustrating. Once again, these differences were not large. This may still be due to the task being overly difficult. However, participants did indicate that performance was better with the foot.

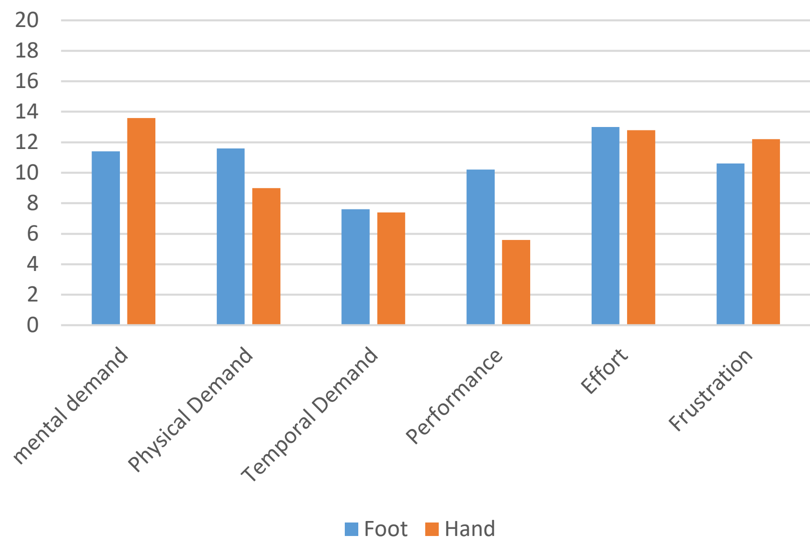

Figure 5.10: SRL experiment modified NASA TLX results for practiced participants are recorded. Scores are rated from low (zero) to high (twenty) with a neutral score of ten. A lower score is better for all metrics except performance.

Performance with the foot interface is faster than the hand for unpracticed participants. For practiced participants, foot control outperforms hand control. This shows that not only can foot control be used for SRLs, but that it can be distinctly advantageous.

6. CONCLUSIONS

This thesis has shown that an SRL can be teleoperated using foot control so that the operator can use both hands and the robot arm to perform a task. Results from 2D positional tasks with the planar interface showed that position control is more effective than rate control with the foot. Position control with the foot covered more distance, faster than rate control with the foot. Position control with the foot was also rated to be easier than rate control. Thus, it is reasonable that position control performs better than rate control because it is easier with the foot, just as it is with the hand.

Results from the final experiment show that a person can operate a foot-controlled SRL while using both hands and thus improve performance. For initial participants, foot control of the arm achieved the same distance as hand control, but was significantly faster for unpracticed users. When new participants were given more practice, the foot also reached a further distance than the hand as well. There is a clear benefit of using foot control of a robot arm when a task is difficult to do with just two hands.

7. FUTURE WORK

Future work should include improving the foot interface for rate control. The spring return for the planar foot interface was relatively slow when compared to a commercial hand interface, and did not have a physical deadband. Improving the spring return may improve user's ability to perform reaching tasks with this control method. The workspace may have also been too large for effective rate control. Reducing the workspace size would solve this. The planar interface could also be improved for position control by adding a clutch or other method to assist in holding still.

Adding more degrees of freedom to the foot device could lead to more versatile arm control. It is still unknown if coordination between the hand and foot can still occur at higher degrees of freedom. If possible, this would aid in the use of foot controlled robot arms in an unstructured environment, such as general assembly. The last experiment could be run again with a simpler task to help determine this.

This thesis focused on isotonic interfaces, which use position as the input. Future work could include testing with isometric interfaces. Isometric interfaces use force as an input, and can reduce fatigue as the operator doesn't have to actually move. This would be particularly advantageous as the leg has larger muscles and greater inertia. This might improve speed of movement as the operator won't get tired as quickly.

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APPENDICES

APPENDIX A

Table A.1: Demographic information is collected from participants of the first experiment.

Number of Participants	6 (M), 2 (F)
Average Age	20.9
Right/Left Handed	7 (R), 1 (L)
Right/Left Footed	8 (R), 0 (L)
Number who play videogames	6
Average number of sports participated in	1

Table A.2: Demographic information is collected from participants of the second experiment.

Number of Participants	10 (M), 2 (F)
Average Age	21.6
Right/Left Handed	11 (R), 1 (L)
Right/Left Footed	9 (R), 3 (L)
Number who play videogames	7
Average number of sports participated in	3.3

Table A.3: Demographic information is collected from participants of the third experiment. Information from regular and practiced participants are included.

Number of Participants	16 (M), 8 (F)
Average Age	32.96
Right/Left Handed	22 (R), 2 (L)
Right/Left Footed	21 (R), 3 (L)
Number who play videogames	13
Number familiar with tilt maze games	17
Average number of sports participated in	1.4

APPENDIX B

The Modified version of the NASA TLX used in experiments 1 and 2.

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

APPENDIX C

The purpose of this program is to teleoperate a Sawyer robot arm. This program reads in values from any input device (not just standard or commercial devices), and uses this input to control the robot arm. It is currently set up to be used with the planar foot interface described above, and modification to the FootJoystickHandler.py file is needed to use other devices.

The Sawyer robot does not have a method to directly control its end-effector position, or orientation. Instead, you must control each individual joint angle. An inverse-kinematic service is available to turn desired position and orientation into joint positions. In order to prevent the robot from continually stopping (resulting in jerky movements), the joint positions must be moved to in a non-blocking fashion. There is a command to do this, but it ignores all collision avoidance measures. Thus, it is up to the operator to ensure no collision will occur. All code dealing directly with the robot is located in LimbHandler.py.

The main file, Main.py, is the link between the joystick and the robot. It maintains two threads. The first thread continually gets updates from the joystick via FootJoystickHandler.py and turns them into the desired position and orientation. These desired values are forced to be within set bounds to ensure safety. The second thread continually sends these desired values to LimbHandler.py which in turn updates the robot's joint angles. Main.py also determines the general functionality of the robot. It is currently set up to move the robot only in the x-y plan with the gripper facing down. Modification is necessary to change this purpose, or to add different motions.

--- Main.py ---

```
#Run this file to run the entire program.  Links the robot arm and the interface
classes.

#Keeps track of where the robot should be.

import rospy
import intera_interface

import threading

from LimbHandler import LimbHandler

from FootJoystickHandler import FootHandler

from asyncore import file_dispatcher, loop

from geometry_msgs.msg import (
   PoseStamped,
   Pose,
   Point,
   Quaternion,
)

class Main:
	def __init__(self):
		#variables used to store desired quaternion
		#current variables are safe place-holders
		self.xPos = 0.623
		self.yPos = -0.06
		self.zPos = 0.17
		self.xQ = 0.998
		self.yQ = -0.02
		self.zQ = 0.07
		self.wQ = 0.004

		#variables used to store joystick output goal
		#current variables are safe place-holders
		self.xGoal = 0.72
		self.yGoal = 0.2
		self.zGoal = 0.3

		#robot bounding box
```

```
        self.xLower = 0.48 #lower bound
        self.xLim = 0.4 #distance from lower to upper
        self.yLower = -0.2#lower bound
        self.yLim = 0.5 #distance to upper bound from lower
        self.zMark = 0.17#want to stay in z plane

        #Limb Handler Object
        self.limbHandle = None

        #Flag used to tell threads to exit
        self.stopFlag = False

        #foot joystick object
        self.footHandle = FootHandler()


    #sets the current pose to match global variables.  Called at the beginning to
    #ensure the program and the robot match.
    def setCurrentPoseGlob(self):
        #get current position
        pose = self.limbHandle.getCurrentPose()
        posInfo = pose.get('position')
        quatInfo = pose.get('orientation')


        #update positions
        self.xPos = posInfo.x
        self.yPos = posInfo.y
        self.zPos = posInfo.z

        #force quaternion to be vertical
        self.xQ = 0.998
        self.yQ = -0.02
        self.zQ = 0.07
        self.wQ = 0.004

        #create locking object to maintain thread safety
        self.lock = threading.Lock()


    #This function will be used to read joystick values
    def readJoystick(self):

        while(self.stopFlag == False):
            (xVal, yVal, bttn) = self.footHandle.getJoystickValues()

            self.zGoal = self.zMark#may want to change this in the future
```

```
        #x movement on joystick is y movement on robot
        if(xVal != None):
            self.yGoal = self.yLower + xVal*self.yLim
        #y movement on joystick is x movement on robot
        if(yVal != None):
            self.xGoal = self.xLower + yVal*self.xLim

        if(bttn == 1):
            self.limbHandle.toggleGripper()



#this function updates the desired positions
def handleDifs(self):
    while(self.stopFlag == False):
        #prevent values from being changed while we use them
        self.lock.acquire()


        #update individual positions
        self.xPos = self.xGoal
        self.yPos = self.yGoal
        self.zPos = self.zGoal

        self.lock.release()
        self.sendRobotCommand()




#this function sends the desired position to LimbHandler
def sendRobotCommand(self):
    #create pose to hand of robot
    pose=Pose(
     position=Point(
        x=self.xPos, #examples:  0.450628752997
        y=self.yPos, #0.450628752997
        z=self.zPos, #0.217447307078
     ),
     orientation=Quaternion(
        x=self.xQ,   #0.704020578925
        y=self.yQ,   #0.710172716916
        z=self.zQ, #0.00244101361829
        w=self.wQ, #0.00194372088834
     ),
  )

    self.limbHandle.moveToPose(pose)
```

```
    #First function that will run in the file
    #handles initialization
    def run(self):
        rospy.init_node("rsdk_ik_service_client")

        self.limbHandle = LimbHandler()

        self.limbHandle.toggleGripper()

        self.setCurrentPoseGlob()

        print('xPos: ', self.xPos)
        print('yPos: ', self.yPos)
        print('zPos: ', self.zPos)



        #Create and start the joystick and update threads
        thread1 = threading.Thread(name='thread1', target=self.readJoystick)
        thread1.start()

        thread2 = threading.Thread(name='thread2', target = self.handleDifs)
        thread2.start()


        #keep from exiting until ctrl-c is pressed
        rospy.spin()

        #joystick thread can't exit unless the joystick is moved while
        #the stop flag is true
        print('\nstopping\n  Jiggle joystick to finish ')
        self.stopFlag = True

        #self.limbHandle.toggleGripper()



#Starts the program
if __name__ == '__main__':
    Main().run()
```

-- LimbHandler.py --

```
#This file sends and receives messages from the robot.

import rospy
import intera_interface

from geometry_msgs.msg import (
   PoseStamped,
   Pose,
   Point,
   Quaternion,
)
from std_msgs.msg import Header
from sensor_msgs.msg import JointState
from intera_core_msgs.srv import(
    SolvePositionIK,
    SolvePositionIKRequest,
)

#This class is used to deal with actual robot control
class LimbHandler:
	def __init__(self):
		self.limb = intera_interface.Limb('right')

		try:
			self.gripper = intera_interface.Gripper('right')
			self.gripper.calibrate()
		except:
			self.has_gripper = False
			rospy.logerr("Could not initalize the gripper.")
		else:
			self.has_gripper = True
			self.gripClosed = False


	#tells the robot to close or open the gripper
	def toggleGripper(self):
		if(self.has_gripper):
			if(self.gripClosed):
				self.gripper.open()
				self.gripClosed = False
			else:
				self.gripper.close()
				self.gripClosed = True

	#returns current pose
	def getCurrentPose(self):
		return self.limb.endpoint_pose()
```

```
#returns desired joint positions to reach pose
def getDesiredPositions(self, goalPose):
	ns = "ExternalTools/right/PositionKinematicsNode/IKService"
	iksvc = rospy.ServiceProxy(ns, SolvePositionIK)
	ikreq = SolvePositionIKRequest()
	hdr = Header(stamp=rospy.Time.now(), frame_id='base')

	poses = {
		'right': PoseStamped(header=hdr,
			pose = goalPose
			),
	}

	#Add desired pose for inverse kinematics
	ikreq.pose_stamp.append(poses["right"])

	#request inverse kinematics from base to "right_hand" link
	ikreq.tip_names.append('right_hand')

	try:
		rospy.wait_for_service(ns, 5.0)
		resp = iksvc(ikreq)
	except (rospy.ServiceException, rospy.ROSException), e:
		rospy.logerr("Service call failed: %s" % (e,))
		return None


	if(resp.result_type[0] > 0):
		#valid solution found
		return resp.joints[0].position

	else:
		rospy.loginfo("INVALID POSE - No Valid Joint Solution Found.")

	return None

#Actually tells the robot to move to the desired pose (joint locations)
def moveToPose(self, goalPose):

	#joint speed can be adjusted
	self.limb.set_joint_position_speed(speed = 0.3)

	curAngles = self.limb.joint_angles()
	positions = self.getDesiredPositions(goalPose)
```

```
        if(positions == None):
            pass
        else:
            angles = self.limb.joint_angles()

            angles['right_j0']=positions[0]
            angles['right_j1']=positions[1]
            angles['right_j2']=positions[2]
            angles['right_j3']=positions[3]
            angles['right_j4']=positions[4]
            angles['right_j5']=positions[5]
            angles['right_j6']=positions[6]

            #sends desired joint values to sawyer
            #NOTE: does not include collision checking
            #           like move_to_joint_positions,
            #but is also non-blocking
            self.limb.set_joint_positions(angles)
            #self.move_to_joint_positions(angles)
```

-- FootJoystickHandler.py --

```
#This file reads in data from the joystick, and sends it to the main file.

#This will need to be updated for each individual device.

from inputs import devices

class FootHandler:
    def __init__(self):

        #Check whether device is listed as a gamepad, or other device
        #set self.device to whichever it is.
        print(devices.other_devices)
        print(devices.gamepads)
        self.device = devices.gamepads[0]

        print(self.device)


        #test values specific to device
        self.minX = -32767.0
        self.maxX = -860.0

        self.minY = -32767.0
        self.maxY = -5051.0
```

```
        '''
        self.rx = (31580-4867)
        self.mx = -18223

        self.dx = self.rx/1000

        self.ry = (28709-8051)
        self.my = -18380

        self.dy = self.ry/1000
        '''


    #returns x and y events.  First value is x, second value is y
    #if x or y events don't fire, returns None in its place
    def getJoystickValues(self):
        events = self.device.read()
        xVal = None
        yVal = None
        bttn = None
        for event in events:
            if(event.code == 'ABS_X'):
                xVal = self.adjustX(event.state)
            elif(event.code == 'ABS_Y'):
                yVal = self.adjustY(event.state)
            elif(event.code == 'BTN_SOUTH'):
                bttn = event.state

        return (xVal, yVal, bttn)


    #converts values to be between 0.0 and 1.0 for ease with position control
    def adjustX(self, x):
        val = (x - self.minX)/(self.maxX - self.minX)
        if(val < 0.0):
            return 0.0
        elif(val > 1.0):
            return 1.0
        return val

    def adjustY(self, y):
        val = (y - self.minY)/(self.maxY - self.minY)
        if(val < 0.0):
            return 0.0
        elif(val > 1.0):
            return 1.0
        return val
```

APPENDIX D

Table D.1: Average, Median, Standard Deviation for Performance Criteria of Experiment 2 is recorded.

		Trial	Mean	Median	STD
Completion Time	Rate Hand	1	73.93	71.10	11.26
		2	68.88	65.54	15.14
	Position Hand	1	52.50	51.18	9.35
		2	51.85	46.88	10.67
	Rate Foot	1	177.38	180.48	25.09
		2	157.11	145.76	43.60
	Position Foot	1	90.50	81.28	25.88
		2	92.81	93.71	22.49
Distance Ratio	Rate Hand	1	1.21	1.20	0.11
		2	1.13	1.12	0.05
	Position Hand	1	1.36	1.36	0.10
		2	1.35	1.30	0.14
	Rate Foot	1	1.31	1.29	0.21
		2	1.30	1.25	0.16
	Position Foot	1	1.52	1.47	0.21
		2	1.50	1.37	0.24

Table D.2: The Mean and Median of each test metric of the third experiment shows similar distance performance between the hand and foot. The foot, however, is faster.

		Mean	Median	Standard Deviation
Distance Traveled (hole fell in)	Unobstructed	12.62	12	5.93
	Foot	7.64	8	6.02
	Hand	7.58	8	5.60
Max Distance Traveled (hole fell in)	Unobstructed	17.6	21	4.84
	Foot	12.47	11.47	6.46
	Hand	13	11	6.13
Time Taken (seconds)	Unobstructed	33.1	29.8	27.0
	Foot	47.5	36.0	39.6
	Hand	69.1	59.7	48.8

Table D.3: Mean and Median for each test metric for practiced participants of the third experiment show an improvement in performance.

		Mean	Median	Standard Deviation
Distance Traveled (hole fell in)	Unobstructed	11.7	12	4.79
	Foot	9.67	9	5.16
	Hand	7	8	4.39
Max Distance Traveled (hole fell in)	Unobstructed	14.1	14	5.04
	Foot	13.4	11	5.08
	Hand	10.6	11	2.72
Time Taken (seconds)	Unobstructed	36.2	29.6	27.5
	Foot	53.7	54.3	24.5
	Hand	51.9	47.4	39.5