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Development of a foot interface to control supernumerary robotics limbs

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Abstract

Supernumerary robotic limbs (SRLs) can be used to provide a person with extra arms to help with difficult tasks. For example, a task that normally requires three hands to complete could be accomplished by just one person with an SRL. One way to control an SRL and still leave both hands available is to use the foot. This paper describes two parts of developing this foot interface: characterizing the range of forces that the foot can apply, and prototyping systems for different control methods. First, a small sample of data was collected to learn how much force the foot can apply in different degrees of freedom including rotations about the ankle and translations of the foot. Typically, the most force could be exerted in plantarflexion. These forces were then used with a kinematic model of the leg to calculate the torques applied by each joint. It showed that, in most cases, the joints at the hip and ankle see the greatest torque.

Two foot devices are currently being developed: a Foot Pedal and a Foot Plate. The former uses rotations of the foot in different directions to control the robotic arm while the latter uses force inputs from a stationary foot. For the Foot Pedal, each degree of freedom was outfitted with a spring return mechanism so that it could be used as a rate control device. Now, when the user relaxes their foot the pedal will snap back to its resting position. For the Foot Plate, software was developed to read and scale the inputs using a six-axis force-torque sensor. Additionally, adjustable scaling was implemented to accommodate users of different abilities. In the future, an experiment will compare the effectiveness of these two devices for both rate and position control methods.

Introduction

Some tasks are difficult to complete without asking someone else to lend a helping hand. In these cases, a useful aid could be a supernumerary robotic limb (SRL) controlled by the user. An SRL is a robot mounted either on or near the user that helps the user with certain tasks [1]. In order to aid in the development of a foot interface to control an SRL, three tasks were completed, each of which is described in detail in the following sections. First, a short experiment was performed to determine the range of forces people can exert with their foot in different directions. Second, the human leg was modeled to examine the torques acting at each joint for different force outputs and movements. Finally, an existing foot interface prototype was altered to be used for different control inputs. Before discussing this work, some background is provided on foot movements and the existing foot interface prototypes.

Foot Movements

The human leg can be modeled with three degrees of freedom in the ankle, one in the knee, and three in the hip. Ankle motion is the most useful in these device applications because it is the most natural and simple movement. Traditional pedals are operated by rotation of the ankle in dorsiflexion/ plantarflexion, as shown in Figure 1 [2]. Typically, more force is exerted when rotating in plantarflexion, which causes a greater torque at the ankle [3]. One study gave mean ranges of motion as 15.3° for dorsiflexion and 30.7° for plantar flexion [4].

Figure 1. The ankle's dorsiflexion/plantarflexion degree of freedom is often used to operate pedals (figure from [4]).

In Lauru's Physiological Study of Motions, several different pedals were compared [2]. The main variable that was compared was the placement of the pivot. The pedal that was the easiest to use had its pivot under the axis of the tibia, in line with the ankle. Since the pedal's pivot was in line with the human foot's natural pivot, Lauru's data shows that this pedal requires the least amount force to activate and can be operated the most quickly [2]. This information was incorporated into the experiment - the pedal was built such that the pivot was in line with the ankle.

The second most commonly used degree of freedom of the ankle is a "side-to-side" pivot using abduction and adduction of the ankle, as shown in Figure 2. According to one experiment, this is said to be the most comfortable foot motion for most people [5]. According to an experiment by Zhong et al., the range of motion of abduction is around 33° and that of adduction is around 53° [6].

Figure 2. The abduction/adduction degree of freedom of the ankle is a "side-to-side" pivot (figure from [4]).

Finally, the ankle can rotate in inversion/eversion, shown in Figure 3. This type of rotation is limited in range of motion (about 27° each direction without moving at the knee) and is not used by itself very often in foot devices, so there is not much literature on it [4].

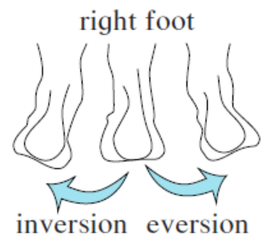

Figure 3. The inversion/eversion degree of freedom of the ankle is the least commonly used for control interfaces (figure from [4]).

Devices

Two devices were designed to control an SRL using either applied leg movements or forces. The first device is the Foot Pedal, which the user can rotate using both plantarflexion/dorsiflexion and adduction/abduction of the ankle. As seen in Figure 4, the device can also slide on a track, but that degree of freedom was not used at all in the context of this paper. Since the input for this device purely comes from the motions of the leg as opposed to the forces it exerts, it is considered an isotonic device [8].

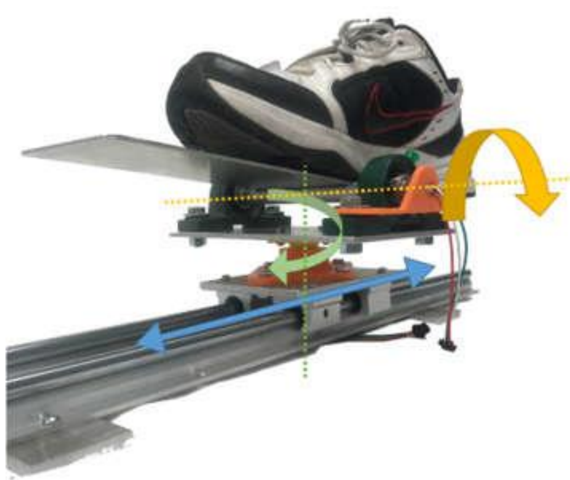

Figure 4. The Foot Pedal is an isotonic device that uses dorsiflexion/plantarflexion and abduction/adduction movements.

The second device is the Foot Plate, which is shown in Figure 5. To use this device, the user keeps their foot stationary on the plate while applying forces in different directions. The Foot Plate is an example of an isometric device because the input comes from forces from the limbs without them actually moving [8].

Figure 5. The Foot Plate is an isometric device that uses input forces and torques in six degrees of freedom.

Experiment

To estimate how much force the foot can exert in different degrees of freedom, a short, informal experiment was conducted. Forces were recorded for different movements for several subjects using the two different devices described previously. The forces found here can determine how fatiguing each motion is and what muscle groups are being used more than others. This information can be used to improve the designs of both devices.

Methods

To measure the forces one would exert on the foot plate apparatus, each subject sat in a chair with their dominant foot on a scale and their knee bent at an angle of approximately 90 degrees. Each subject was instructed to sit comfortably with their backs mostly straight as they would sit at a desk to work. The resting foot weight was measured as the approximate scale reading of each subject sitting in this position. For the rest of the trials, subjects were instructed to stay seated with most of their weight on the chair. For dorsiflexion and plantar flexion, the subject moved their foot so that their heel or toe, respectively, was centered on the scale for the most accurate weight reading. The subject was instructed to press on their heel or toe in a way that they were still comfortable – subjects were not to bear down on their foot on the scale. For inversion and eversion, subjects put their foot back in the center of the scale and rolled their ankle out in the respective direction and pushed down, again not bearing down with their weight but just comfortably pressing. The values recorded for each subject are listed in Table 1 below.

To measure the forces one would exert on the foot pedal apparatus, each subject sat in a chair with their foot positioned on the pedal so that the pivot point was aligned underneath their ankle. This pivot location has previously been found to require the least amount of force to activate, and therefore would be less fatiguing than any other pivot location [2]. For plantar flexion, the scale was placed on the track under the front of the pedal and the subject pressed down with their foot as done in the foot plate trials. Dorsiflexion was not tested for this apparatus because it couldn't be measured due to the much shorter length of the pedal behind the pivot. For rotation in either direction, the scale was propped up against the wall or a nearby chair. It was zeroed and the subject was then instructed to rotate their foot on the pedal so that the pivoting plate was pressing against the scale. This action was performed for both abduction and adduction rotation. Finally, the force exerted by sliding the pedal along the track was measured. The scale was set up nearly vertically against a wall. The subject sat facing the wall and slid the pedal into the scale so they were comfortably applying force while remaining seated. The values are recorded in Table 2.

Results

As seen in Table 1, every subject could exert the most force when pressing straight down as opposed to rotating their foot in any direction. For every subject except Subject 4, the force exerted was close to equivalent for each degree of rotation. These results can also be seen graphically in Figure 6.

Table 1. The forces (Newtons) were measured for each of the movements that would be used on the Foot Plate device.

Subject	Resting Foot Weight	Dorsiflexion (heel)	Plantar flexion (toe)	Inversion (out, right)	Eversion (in, left)	Pressing straight down
1	35.6	64.5	62.3	68.9	57.8	84.5
2	62.3	124.6	106.8	126.8	137.9	146.8
3	44.5	75.6	75.6	84.5	80.1	106.8
4	86.7	155.7	173.5	89.0	75.6	177.9
Avg.	52.3	105.1	104.6	92.3	87.9	129.0

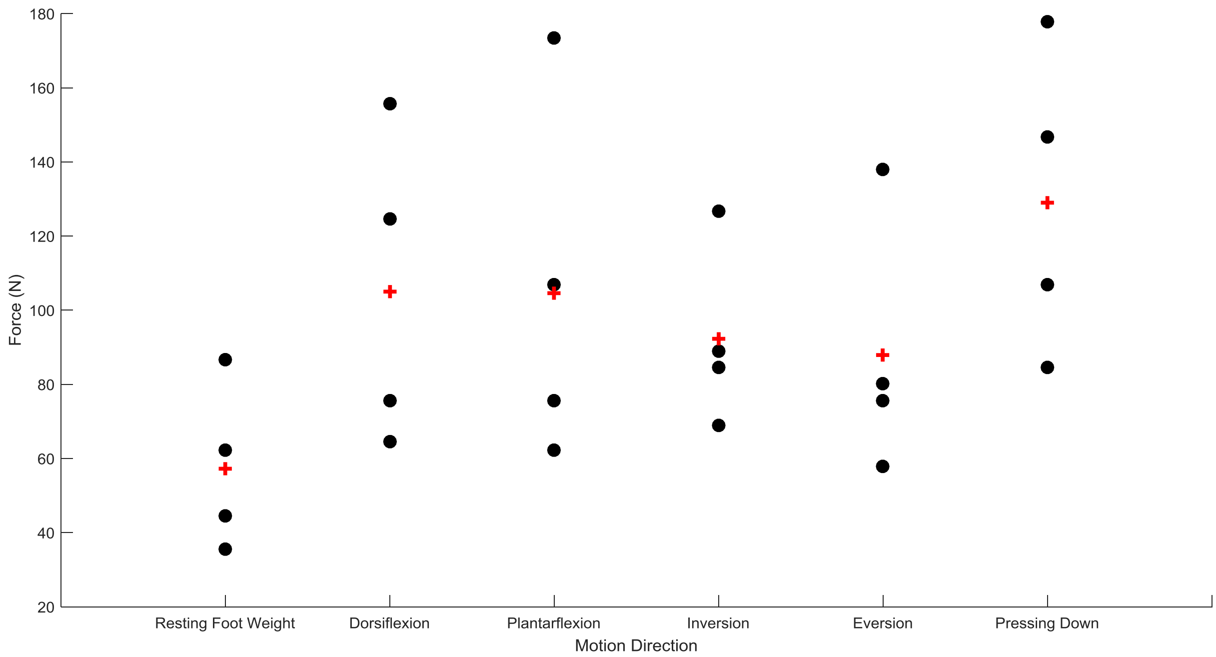

Figure 6. The results from Table 1 were graphed such that each dot represents a subject's force output in a given direction and each red cross represents the average force exerted in that direction.

Based on these results, using the inversion/eversion degree of freedom does not appear to be optimal because the possible ranges of forces were so small, and the averages were lower compared to the other degrees of freedom.

For forces measured for the Foot Pedal, as shown in Table 2, plantarflexion was always stronger than adduction and almost always stronger than abduction too. Adduction was typically the weakest force, and the force exerted by the forward sliding motion was almost always the strongest. These results can also be seen graphically in Figure 7.

Table 2. The forces (Newtons) were measured for each of the movements that would be used on the Foot Pedal device.

Subject	Resting Foot Weight	Plantar flexion (front)	Adduction (in)	Abduction (out)	Sliding forward
1	35.6	31.1	26.7	31.1	57.8
2	62.3	80.1	53.4	48.9	53.4
3	44.5	44.5	31.1	48.9	80.1
4	86.7	62.3	35.6	53.4	120.1
Avg.	52.3	54.5	36.7	45.6	77.9

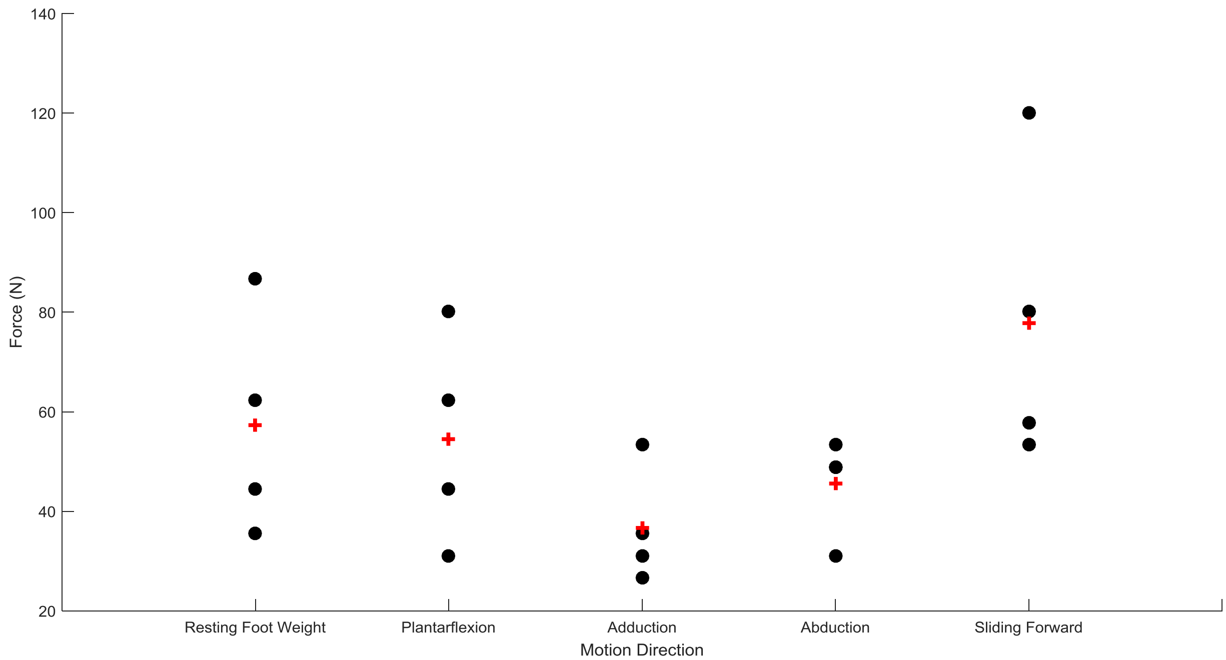

Figure 7. The results from Table 2 were graphed such that each dot represents a subject's force output in a given direction and each red cross represents the average force exerted in that direction.

Based on the results for the Foot Pedal, the abduction/adduction might not be optimal for this application because the possible ranges of forces were so small, and the averages were lower compared to the other degrees of freedom.

Comparing the results for these two setups, it can be seen that larger forces can be exerted on the Foot Plate than on the Foot Pedal, potentially because the foot is stationary. This means that the Foot Plate will probably be less fatiguing than the Foot Pedal, which makes sense because the user does not have to move their leg. The Foot Plate also saw a larger range of forces, meaning that it will likely need to be calibrated differently for different people.

Model

The forces found in the experiment were then used with a kinematic model of the leg to determine the torques acting at each joint. This model was created using a series of revolute joints connected by rigid links.

Background

In order to determine the torques acting at each joint when the foot performs the motions used to control either the Foot Pedal or the Foot Plate, a static model of the leg was developed. A similar process was followed as discussed by Hernández-Santos [9]. The model was used to calculate joint torques for specific movements were found using the maximums of the forces found in Table 1 and Table 2.

Analysis

The leg was modeled as a series of revolute joints to represent the hip, knee, and ankle joints. First, a static analysis was performed using only the degrees of freedom in the sagittal plane, as shown in Figure 8.

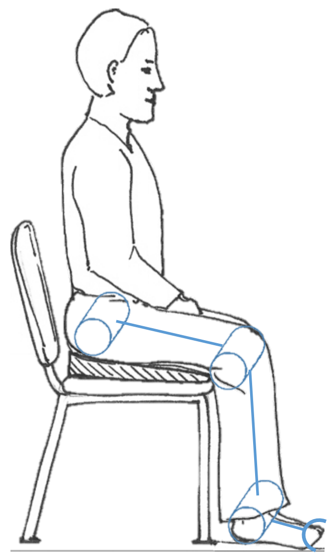

Figure 8. Looking at the leg only in the sagittal plane, the leg can be simplified down to a series of 3 revolute joints with the foot as the "end effector" (figure from [10])

Coordinate frames were added to this system of joints and linkages following Denavit-Hartenberg (DH) convention, as shown in Figure 9. The joint representing the hip was treated as a fixed joint as if the person was sitting. Each of the three link lengths, l_1, l_2, and l_3, are averages of a set of anthropometric data [11].

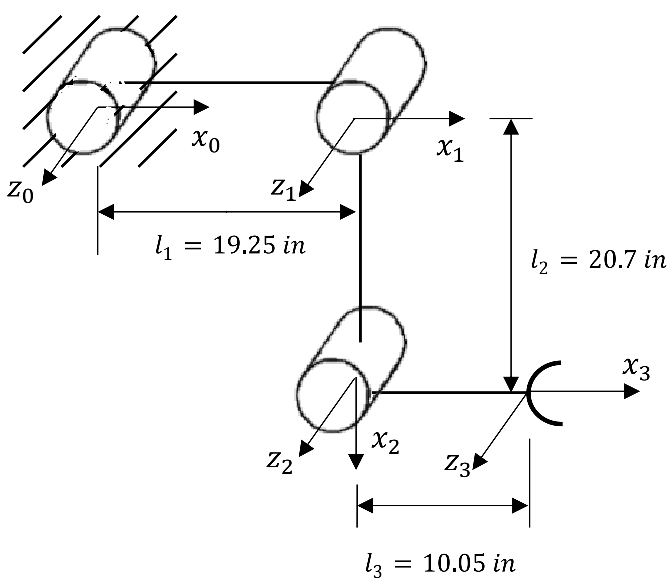

Figure 9. Coordinate frames were assigned to each joint using the DH convention.

The DH parameters were then determined and can be found in Table 3.

Table 3. Denavit-Hartenberg parameters were found for the partial model of the leg.

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	l_1	0°	0	0°
2	l_2	0°	0	-90°
3	l_3	0°	0	90°

The transformation matrices between the frames were computed so the statics problem could be solved using the Jacobian method. For a given force acting at the end effector (i.e. the person pushing down with their toes in plantarflexion), the torque at each joint was returned and recorded in Table 5. The input force was based on the results of the force experiment recorded in Table 2.

Table 5. Maximum forces found in the aforementioned experiment were used to calculate torques at each joint for the leg movements valid in this plane.

Movement	Hip Torque (N-m)	Knee Torque (N-m)	Ankle Torque (N-m)
Plantarflexion	132.4	45.4	45.4
Dorsiflexion	115.9	39.7	39.7
Sliding Forward	93.6	93.6	0

The same process was repeated for a more complex model with spherical joints at the hip and ankle. These spherical joints are modeled here as 3 revolute joints in a row. While they are depicted with space between them in Figure 10, they are treated as joints with a distance of zero between them.

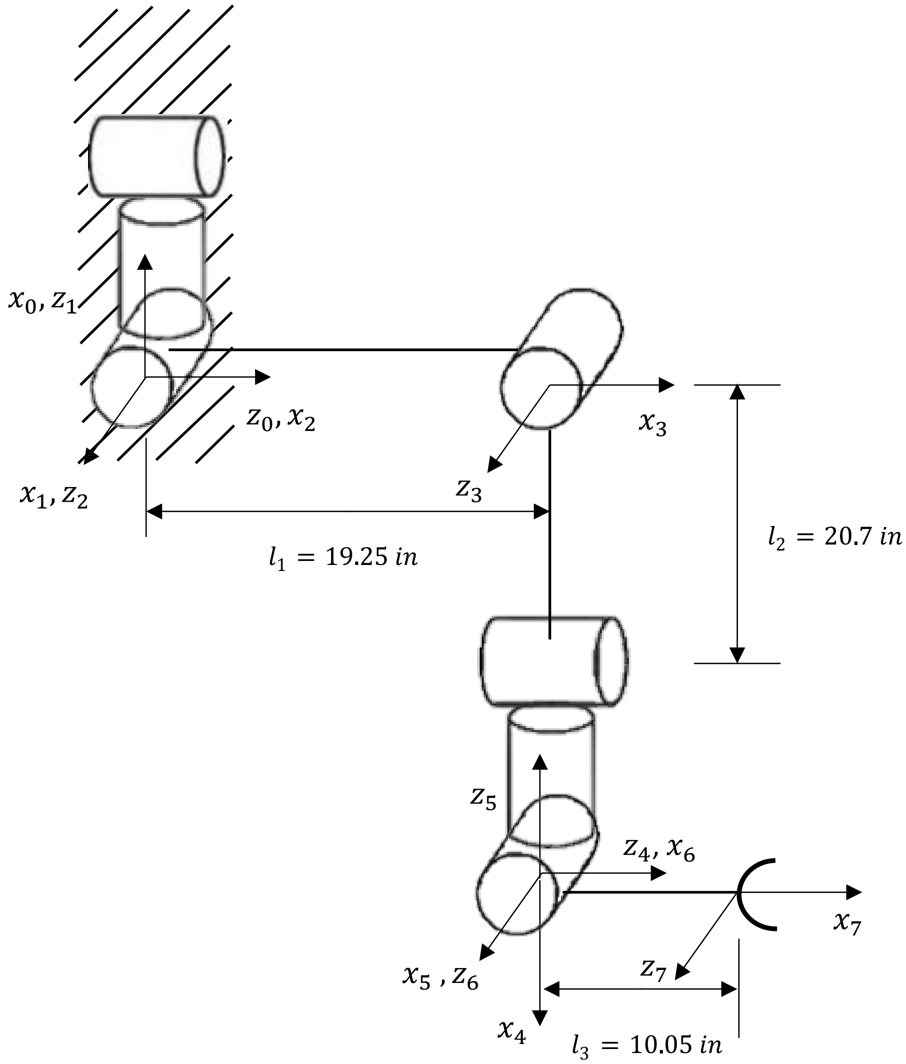

Figure 10. A full model of the leg was created by using revolute joints to represent each degree of freedom.

The top three revolute joints represent the spherical hip joint, and the bottom three represent the spherical ankle joint. The DH parameters were found and have been recorded in Table 4.

Table 4. Denavit-Hartenberg parameters were determined for the full model of the leg.

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	90°	0	90°
2	0	90°	0	90°
3	l_1	0°	0	0°
4	l_2	-90°	0	-90°
5	0	90°	0	-90°
6	0	90°	0	90°
7	l_3	0°	0	0°

After computing the forward kinematics and Jacobian, the resulting torques for the movements discussed previously were calculated and can be found in Table 5.

Table 5. Maximum forces found in the aforementioned experiment were used to calculate torques at each joint for the leg movements described.

	Hip Torque (N-m)			Knee Torque (N-m)	Ankle Torque (N-m)		
Movement	Adduction/ Abduction	Lateral/ Medial Rotation	Flexion/ Extension	Flexion/ Extension	Inversion/ Eversion	Adduction/ Abduction	Plantarflexion/ Dorsiflexion
Plantarflexion	0	0	132.4	45.4	0	0	45.4
Dorsiflexion	0	0	115.9	39.7	0	0	39.7
Inversion	34.1	0	0	0	34.1	0	0
Eversion	34.1	0	0	0	34.1	0	0
Abduction	35.1	49.7	0	0	0	17.0	0
Adduction	30.4	43.0	0	0	0	14.8	0
Sliding Forward	0	0	93.6	93.6	0	0	0

Overall, the hip exerts the most torque and the knee exerts the least. Dorsiflexion and plantarflexion cause the most torque while inversion and eversion cause the least. Torque at the hip should not cause an overwhelming amount of fatigue because it is supported by the chair as the person sits.

Design

Background

Two control input methods used in various applications are position control and rate control. With position control, the user directly controls the position of whatever object they are moving. With rate control, the velocity of the object is proportional to the user's input [12]. For reaching tasks, it has been found that hand interfaces are more effective when using position control instead of rate control [12, 13]. However, since foot interfaces are still much less common overall, there is not much literature comparing rate and position control for such a device. This information is critical for developing the best possible apparatus for controlling a supernumerary robotic limb with the foot. The Foot Pedal is already an effective position control device, but several steps must be taken so that it can also be used as a rate control device in order to compare the two control methods.

In addition to just comparing rate and position control for an isotonic device like the Foot Pedal, it is useful to compare these two input methods for an isotonic device, the Foot Plate, and to compare each input method for each device in order to find the best combination. Isotonic and isometric devices have been previously compared for hand interfaces, showing that an isotonic device with position control and an isometric device with rate control are more effective than the other combinations [8]. There is significantly less research on this topic for foot interfaces, although one study by Abdi et. al found that people can complete tasks with a foot-controlled hand in coordination with their own two hands given some practice [1].

Foot Pedal

The original model of the Foot Pedal works well as a position control device because the user can move their foot in the different degrees of freedom and the virtual cursor will move proportionally to how much they move their foot. While the Foot Pedal could be used for a rate control input, it would be difficult to stop the cursor from moving once it is at its desired location. The user would have to balance their foot at the center point of each degree of freedom. To give the user an easier way to stop cursor movement, each rotating degree of freedom was outfitted with a spring return.

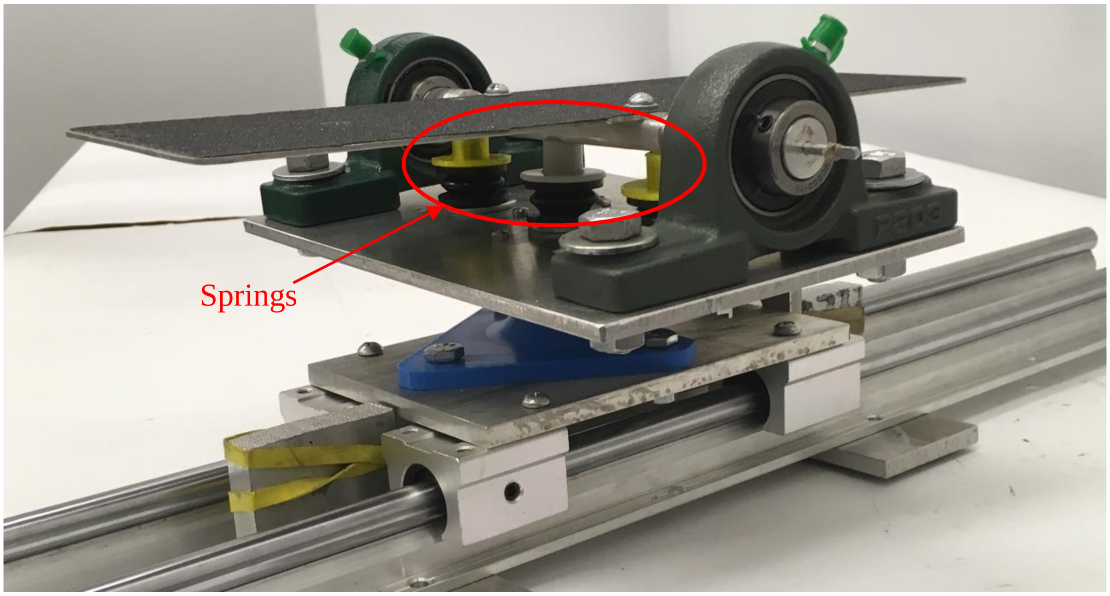

Figure 11. The Foot Pedal apparatus was outfitted with spring returns.

In the dorsiflexion/plantarflexion direction, the design was based off of the mechanism in a typical hand joystick. A joystick tends to "snap" back to the center position when the user stops applying force to it. That same feeling was targeted for the spring returns on the Foot Pedal. To achieve this, the springs are set up so that they are each initially compressed some when the pedal is in its default position. This preload accounts for the weight of the user's leg resting on the pedal and makes the user have to exert more force in order to compress the spring. Because plantarflexion is also the ankle rotation that causes the most torque, a much greater spring stiffness was needed than that of the hand joystick [3]. There is not very much room between the pivot point and the base plate and it would be uncomfortable for the user if the pedal was moved up any more, so three short springs were placed in parallel to provide a total equivalent stiffness of about 59893 N/m.

In the abduction/adduction direction, the spring return design was a bit more complex. There was less room below the pedal surface to mount a spring return. Additionally, the spring could not be mounted directly to the pivot point for this degree of freedom due to the original design. The spring was mounted in the front of the pedal, but it was not secured well enough for this degree of freedom to "spring back" as well as the other direction did. Work to improve this spring return system will be done in the future.

Foot Plate

The alternative device, the Foot Plate, uses force input to control the robotic limb. To prepare for this device, a six-axis force-torque sensor was set up so that a computer can receive data from it via serial communication. For use with the reaching game, both position and rate control algorithms were developed using the force inputs. For isometric position control, as the user inputs more force in one direction, the cursor moves further in that direction. For example, pushing directly away from oneself would move the cursor up the screen vertically. When the user stops applying force, the cursor moves back to its home position. For isometric rate control, as the user inputs more force in one direction, the cursor moves faster in that direction. When they stop applying force, the cursor stops moving at the location it was in. The algorithms also feature adjustable force scaling. Since different individuals can generate different amounts of force, the input from the sensor can be scaled so that it takes either more or less force to reach certain positions or speeds. The user can adjust this scaling factor while performing the reaching task.

Conclusion

There is a lot of literature about hand interfaces to control robot arms. There has been much less research done about equivalent foot interfaces, and since the feet operate very differently than the hands there is no guarantee that different styles of devices or control methods are as effective. This paper highlights some information that is useful in creating the best possible foot input device.

Collecting a small set of data on how much force humans can exert with their foot in different degrees of freedom has allowed us to examine the torques applied to each joint during these movements. From there, it can be seen which inputs to the Foot Pedal and Foot Plate are most fatiguing on different joints so we can select degrees of freedom that will be the most comfortable for the user. The results showed that, while plantarflexion/dorsiflexion is the most commonly used movement, it causes the most torque on the leg joints and is likely the most fatiguing motion. Adduction and abduction are the least fatiguing, which supports the statement that they are typically the most comfortable motions [5].

Additionally, we want to find the optimal style of input device and the best control method to use with it. Now that the Foot Pedal has spring return mechanisms that can be removed, the device is ready to be used in a study to determine if rate or position control is more effective for an isotonic foot interface. This information could also be compared to how effective each control method is for hand interfaces – will both interfaces show the same trends? Similarly, once an interface to use the foot with the force-torque sensor has been finished, a study could be conducted to research the difference between rate and position control with an isometric device. Again, these results could be compared to a similar study involving a hand interface. Information from studies of both devices could be put together to compare each method of control for each style of device.

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