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Stroke Survivor Gait Adaptation and Performance After Training on a Powered Ankle Foot Orthosis

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Abstract— **With over 600 thousand people each year surviving a stroke, it has become the leading cause of serious long-term disability in the United States [1], [2]. The adverse financial and social conditions attributed to stroke have prompted researchers and entrepreneurs to explore the viability of rehabilitation robots. The Powered Ankle Foot Orthosis (PAFO) utilizes robotic tendon technology and supports motion with a single degree of freedom, ankle rotation in the Sagittal plane. Motion capture data, robot sensor data, and functional 6 minute walk data were collected on three stroke subjects. All subjects had some positive changes in their key gait variables while using the PAFO. These changes were more dramatic while harnessed and using a treadmill as opposed to walking over ground. Robot sensor data showed significant improvements on key variables for the three subjects. Motion capture data showed improvements in knee range of motion for subject 1, and the 6 minute walk data showed an increase in distance walked for subjects 1 and 3. Comfort, stability, and robustness proved to be critical design parameters for developing a gait therapy robot capable of collecting repeatable data with low variability.**

I. INTRODUCTION

With over 600 thousand people each year surviving a stroke, it has become the leading cause of serious long-term disability in the United States [1], [2]. This figure is expected to more than double within the next 50 years. This prediction is based on the elderly population growth rate that is 35 times faster than the general population, the explosion in the number of obese adults in the United States, and advances in medicine causing an increase in stroke survival rate [3], [1], [2], [4], [5], [6].

The adverse financial and social conditions attributed to stroke have prompted researchers and entrepreneurs to explore the viability of rehabilitation robotics. Gait therapy is a natural place to start as statistics show that post-stroke, only 37% of stroke survivors are able to walk [7]. Of those patients with initial paralysis, only 10% regain functional independence post-stroke [8]. Among stroke survivors who are not initially paralyzed, 25% do not regain the ability to use their affected leg and walk. These alarming statistics justify the need for rehabilitation devices and techniques that are highly effective in aiding patients to overcome the ill effects of stroke [9], [10].

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The objective of this paper is to present the findings and challenges of a case study where 3 stroke survivors trained on a 1 degree of freedom, robotic tendon actuated, powered ankle foot orthosis (PAFO) for 3 weeks. The data presented will be from sensors mounted on the robot, from a 6 camera HiRes motion capture system, and from a 6 minute walk test.

II. ROBOT BACKGROUND

The Powered Ankle Foot Orthosis (PAFO) was developed with a single degree of freedom, ankle rotation in the Sagittal plane. This rotation is actuated by the Robotic Tendon, which is a DC motor coupled in series with a spring [11], [12]. Gait assistance is provided at a 50% level from the robot. Control commands are derived from position feedback on the input side of the spring, while the output side is open-loop. The control architecture coupled with the series spring makes the Robotic Tendon actuator naturally compliant. Additionally, the reference pattern for the proximal side of the spring is generated such that the elastic elements are stretched at the proper time to produce the desired ankle moment pattern [13]. A major challenge of developing a custom fit PAFO was integrating the motor, lever arms, and sensors to the polypropylene copolymer orthosis. Details of the design can be seen in Fig. 1. For more detail on the design and previous control strategies of this robot see the following reference [14].

Other wearable devices include a pneumatically actuated lower limb orthosis developed at University of Michigan, and a robotic ankle foot orthosis powered by a series elastic actuator developed at MIT [15], [16]. Alternative approaches to gait therapy can be seen in devices like the Lokomat and Haptic walker; they are large, direct drive systems that simulate compliance through complex control algorithms [17], [18].

III. SUBJECT TESTING METHODS

To truly evaluate the effectiveness of the PAFO as a therapy device, stroke subjects must use the device while functional, kinematic and kinetic data are collected. This protocol involves two components, training and testing. The research protocol was approved by the IRB at Washington University in St. Louis where the testing was performed. See table I for details of the subjects that have participated in this study. Key inclusion criteria included being able to: stand independently for two minutes, move from sit to stand, walk 7 meters 10-15 times with rest, demonstrate adequate motion of the lower limb joints, and follow simple commands. Subjects were allowed to use their normal walking aids

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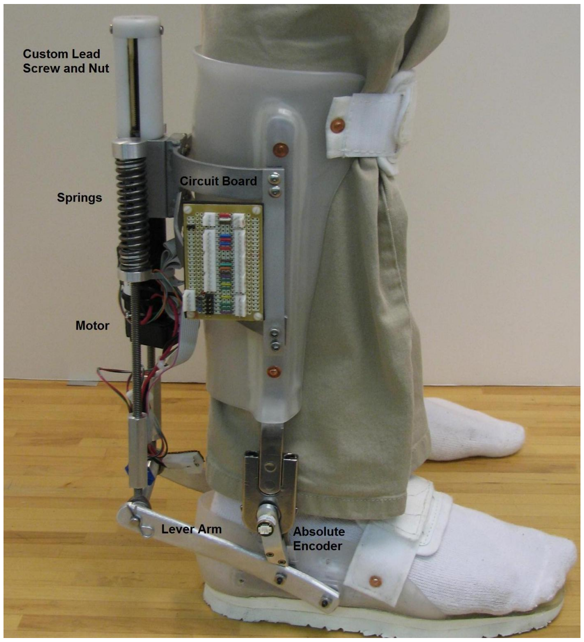

Fig. 1. Custom designed PAFO

TABLE I
SUBJECT INFORMATION TABLE

Subject #	1	2	3
Age (yr)	60	48	48
Sex m/f	f	m	m
Weight (kg)	81.6	93.0	79.4
Height (cm)	152	183	178
Affected Side L/R	L	L	R
# Months Post Stroke	204	240	300
Custom or Scalable PAFO C/S	S	S	C

if necessary. Key exclusion criteria included any serious medical condition and excessive pain.

All subjects trained three times per week for three consecutive weeks. The training session consisted of five components: 1) warm-up (five minutes), 2) over ground gait pre (six minutes), 3) treadmill gait (twelve minutes), 4) over ground gait post (six minutes), and 5) cool-down (five minutes). During warm-up and cool-down, the subjects performed some light stretching mainly focused on the lower extremities (calves, hamstrings, and quadriceps). Both the over ground and treadmill walking consisted of wearing and not wearing the PAFO. The actual treadmill training with the PAFO focused on improvement in gait kinematics and increasing gait speed and duration. Any compensatory motions on the unaffected side as well as the trunk and pelvis were addressed by the therapist.

The testing component involved a gait analysis outcome test which occurred during two sessions (pre- and post-training) for each subject. These sessions consisted of two parts, not wearing and wearing the PAFO, with reversed order for the second session. Kinematic data were collected from both sessions with a motion capture system at a rate of 60 Hz. Three surface markers were placed on the trunk, pelvis, thighs, legs, and feet in a standardized method [19], [20]. For each session the subject was asked to walk at their freely chosen walking speed while six to eight trials of data were collected. Motion capture analysis produced walking speed, stride length, and cadence data for each subject as well as lower limb sagittal plane kinematics. Twelve to fifteen complete gait cycles taken from the 6 to 8 trials were used to produce average curves.

Another source of data came from the sensors on the robot. The robot measures the deflection of the spring to calculate the force applied by the robot to the ankle, measures ankle angle from an absolute encoder, determines heel strike from a force sensing resister, and records the angular velocity of the shank from a rate gyro. From these sensors, several key gait metrics can be evaluated. It should be noted that no statistical analysis was performed on either the robot data or the motion capture data to generalize individual subject results to a broad population, because evaluating the number of replicates, or subjects required for statistical significance is out of the scope of this project. However, statistical analysis was performed on key variables for each individual subject.

IV. RESULTS AND DISCUSSION

The results are separated into two parts, robot assisted gait, and unassisted gait. First, key evaluation metrics for analysis of the robot sensor data will be described. Then, sections IV-B and IV-C present the results for robot assisted gait from sensor data collected on the robot during the study. Finally, section IV-D presents the results for unassisted gait as determined by functional measures (6 minute walk test) and motion capture data.

A. Key Performance Metrics Defined for PAFO Sensor Data

There are a total of 11 key metrics that have been examined for each subject training with the Powered Ankle Foot Orthosis (PAFO). These variables were recorded for every step in a trial. The means and standard deviations were calculated for each variable over the total steps taken per day. Beginning with subject 3, these data are divided by day and also by whether the subject walked over ground or on the treadmill. It is important to note that kinematic variables (Maximum Dorsiflexion, Plantarflexion, and Range of Motion) are listed in units of millimeters. This is the length of travel of the lever arm on the robot, and correlates to degrees:

$$Degrees = (LeverArmTravel/LeverArmLength) * 180/\pi$$

The sine term is neglected without significant errors due to small angular travel.

- Key Performance Metrics
  1) Cadence (steps/min)
  2) Maximum Dorsiflexion (mm)
     - Maximum positive ankle angle in terminal stance.
  3) Gait % at Maximum Dorsiflexion (%)
     - % of stride time at maximum positive angle.
  4) Maximum Plantarflexion (mm)

- Largest negative ankle angle at toe-off.

5) Gait % at Maximum Plantarflexion (%)
   - % of stride time at largest negative angle.
6) Range of Motion (mm)
   - Max Dorsiflexion - Max Plantarflexion.
7) Maximum Ankle Moment (Nm)
8) Gait % at Maximum Moment (%)
9) Mechanical Power Output (Watts)
   - Maximum power output, force in robot springs x velocity of the ankle.
10) Gait % at Maximum Power Output (%)
11) Power Amplification (Power Out/Power In)
    - Ratio of maximum power output divided by the mechanical power supplied by the robot. Mechanical power supplied by the robot equals force in robot spring x velocity of the linear actuator.

B. Robot Assisted Gait Data Results - Subjects 1 and 2

The robot data collected and presented here indicates both a measure of robot performance as well as subject adaptability to robotic gait influences. The first two subjects used the previously designed scalable, one size fits all, PAFO. For this reason, their performance will be evaluated separately from the third subject. Due to the mechanical structure of the scalable robot, both subjects wore foam padding under the shoe of their unaffected leg to even the height of both feet. Additionally, the footbed was made of rigid plastic and only extended to the end of the metatarsals, just before the proximal phalanges. These facts led to a performance reduction in all key metrics as well as increased variability when compared with subject 3. Despite the limitations of the previous robot, some noteworthy results were recorded.

Robot sensor data were collected for every training day. For accurate comparison, only training days that had at least twenty good data points, or steps, were used. Otherwise, the data for that day were rejected. Table II summarizes the results of all key metrics for subject 1. The "pre" column is the mean value of the metric on the first training day, followed by its standard deviation, and the "post" column is the mean value of the metric recorded on the last training day followed by its standard deviation. The "Delta" column is the difference between "post" and "pre." The "Ttest" column tests the null hypothesis that the "pre" data and "post" data come from distributions of equal means. A value of 1 in the "Ttest" column means the null hypothesis can be rejected at the 1% significance level, conservatively signaling the means are not equal, whereas a 0 indicates equal means. The "Typ Values" column lists the mean values of an able-bodied male subject, weighing 76.2 kg, walking with the PAFO at similar speeds. These values were listed in place of the able-bodied data published by Whittle to more accurately reflect able-bodied responses to wearing a PAFO [21].

For subject 1, the key performance metrics are given in table II. Notice the reduction in the standard deviation for all variables except peak power output where the increase in the standard deviation was very slight. This suggests that the subject became more comfortable wearing the robot as her measured gait variables became more consistent. The significant findings from the table, as highlighted by the 1 in the "Ttest" column, are:

1) Mean pace increased from 24 to 27 steps/min.
2) Maximum dorsiflexion values reduce in variability and increased in amplitude from -0.9 mm to 1.4 mm, equivalent to a 1.5 degree increase.
3) Range-of-Motion was increased 3.2 mm, or 2 degrees.
4) Maximum Moment increased from 16.3 Nm to 19.5 Nm with reduced variability.
5) Peak Power out increased from 7.5 to 14 Watts.

The increased dorsiflexion amplitude, which primarily contributed to the increase in overall range-of-motion, for subject 1 suggests that by the end of the study she was able to store more energy in the robot's elastic elements. This idea is supported by the increases in peak moment and peak power out. The amplitude increase in peak moment is only partly attributed to an increase in gait speed, as our first subject increased her speed by 12% while her ankle moment increased by 20%. While this is encouraging, the peak power out values are still very low. This is primarily attributed to slow walking, which requires much less power. Despite the slow walking, the first subject was able to increase her gait power by an impressive 89%.

Refer to table I for a description of subject two, and table III for a list of his key metric values. There are also many significant changes in the key metrics of subject 2:

1) The standard deviation reduced for variables: peak moment; maximum dorsiflexion; and % gait at maximum dorsiflexion, plantarflexion, and peak power.
2) Mean pace increased from 35.2 to 39.6 steps/min.
3) Max dorsiflexion dropped from -2.5 mm to -3.7 mm, or a total of 0.76 degrees.
4) Max plantarflexion changed from -6.4 mm to -21 mm, an amplitude increase of 9.3 degrees.
5) Range of motion increased by 13.2 mm, or 8.4 degrees.
6) Peak moment decreased from 31.8 Nm to 17.4 Nm.
7) % gait at peak moment reduced from 64.9% to 51.3%.
8) % gait at peak power reduced by 4.9%, to 56.3%.
9) Power amplification ratio grew 0.7 to 1.5.

For subject 2, the overall range of ankle motion increased by 13.2 mm, or 8.4 degrees. This is primarily due to a large increase in plantarflexion amplitude (dorsiflexion was reduced). Additionally, despite the reduction in maximum ankle moment and output power not significantly changing, the user's power amplification significantly increased to 1.5. This was accompanied by a reduction in % gait at peak moment. The % gait at peak moment is trending toward able-bodied results. These facts suggests that the contribution of power from the user increased throughout the study.

Both subjects used the previously designed and scalable robot that was plagued with fit and performance issues. Although there were some variables that indicate improvement, there are others that indicate reduction. The external factors

TABLE II

SUBJECT 1 KEY METRICS

	pre	(+/-) Std	post	(+/-) Std	Delta	Ttest	Typ PAFO Values
pace in steps/min	24.1	0.2	27.0	0.1	2.9	1.0	33.1
Max Dorsiflexion (mm)	-0.9	1.8	1.4	1.3	2.3	1.0	10.3
% of Gait @ Max Dorsi-	47.7	8.2	49.3	1.9	1.5	0.0	39.8
Max Plantarflexion (mm)	-6.5	1.8	-7.4	0.2	-0.9	0.0	-19.3
% of Gait @ Max Plantar-	67.2	5.9	68.4	5.5	1.2	0.0	64.6
Range of Motion (mm)	5.6	1.6	8.8	1.4	3.2	1.0	29.6
Peak Moment (Nm)	16.3	5.6	19.5	1.5	3.2	1.0	30.2
% of Gait @ Peak Moment	56.7	7.9	51.7	1.5	-5.0	0.0	42.1
Peak Power Out	7.5	2.3	14.2	2.7	6.7	1.0	22.4
% of Gait @ Peak Power	43.9	29.5	53.5	1.3	9.7	0.0	49.6
Power Amplification (ratio)	1.6	0.5	1.9	0.3	0.3	0.0	1.9

like poor robot fit and lack of robustness make it difficult to draw any concrete conclusions from these data.

C. Robot Assisted Gait Data Results - Subject 3

Subject 3 was the first user of the custom fit PAFO shown in figure 1. The advantages of using a custom robot is a more comfortable and secure fit, and a flexible foot-bed that allows a more natural progression of the center of pressure on the foot as opposed to a rigid plastic foot-bed. Additionally, the foot-bed height matches the height of the subjects' normal shoes worn during training (increases subject stability), and the custom fit allows for more uniform loads on the subject as the robot is not deforming around the shank. The following data are broken into treadmill testing, and over ground testing. The subject's performance was markedly different under each condition. While on the treadmill the subject had the comfort of knowing he was protected from a fall with a harness, and had a rail that he could hold onto if he began to feel unstable. Table IV shows the pre- and post-results for all the key metrics for over ground walking while table V lists these results for treadmill walking.

For over ground data, cadence had a slight increase of 2.3 steps/min over the course of the entire study. In contrast, the treadmill data shows a dramatic jump to 45.6 steps/min by the end of the study. This is the likely result of the confidence the subject had while being harnessed on the treadmill, and having the ability to hold onto a rail if he felt unstable.

The affected ankle kinematics improved, according to robot sensor data, over the course of the study for subject 3. During over ground gait, no significant change was observed in maximum dorseflexion. However a 28% increase in maximum plantarflexion was observed. This put the subject's plantarflexion values on par with "typical values" seen for this metric. These results led to a range of motion increase of 5 mm, or 3.2 degrees for over ground data.

For treadmill data the results were again more dramatic. The subject improved all kinematic parameters, maximum dorsiflexion grew to 11.5 mm while plantarflexion amplitude grew to 19.2 mm, increasing the ankle range of motion by 48% to 19.5 degrees. Subject 3 had an ankle range of motion on par with "typical values" seen by other able-bodied users of the PAFO.

Ankle kinetic data demonstrated very different results for over ground verses treadmill. The over ground showed significant change only in peak moment, which was decreased by 1.6 Newton meters. It should be noted that peak power and moment data had a significant drop on the last day of training, as compared with the day before. If the prior day was considered the last day of the study, significant increases would have been seen in both variables. The cause for this drop on the last day of therapy are unknown. The over ground data are typically more variable than the treadmill data.

In contrast, the treadmill results were very positive. Peak moment increased by 10 Nm, and peak power increased by 23.6 W while power amplification was reduced by 0.5. This suggests that on this day, the increases in gait speed were the primary factors of the increases in power and moment, and the subject was relying more on the robot to generate these kinetics. This was not the case during the entire study. Although peak power on the last day increased from the first trial, there was a significant reduction when compared with the prior day. This reduction dropped the power amplification factor. The power amplification factor was 2.4 on 6/6/2009, and floated around "typical values" of 1.9 for the entire study with the exception of a very large spike on 5/19/2009.

The over ground data for both gait % at maximum dorsiflexion and plantarflexion are highly variable. T-test analysis shows that the 1.8% reduction in gait % at maximum dorsiflexion is significant. For treadmill data both variables were significant, with gait % at maximum dorsiflexion moving 6% closer to "typical values," but gait % at maximum plantarflexion moves away from "typical vaules" by 1.3%.

The timing for peak moment and peak power improved in both the over ground and treadmill case. The over ground case had much higher variability, but still showed significant reductions in gait % at peak power and moment occurance. These values trended toward "typical values." Again, the timing for the treadmill case was closer to "typical values" than the over ground case. Stroke gait is typically characterized by delayed moment and power generation.

In conclusion, the robot sensor data analysis for subject 3 had a significant change for every key metric from the treadmill data. For the over ground data, there were 7 of the 11 variables that had a significant change. While on

TABLE III

SUBJECT 2 KEY METRICS

	pre	(+/-) Std	post	(+/-) Std	Delta	Ttest	Typ PAFO Values
pace in steps/min	35.2	0.1	39.6	0.1	4.4	1.0	33.1
Max Dorsiflexion (mm)	-2.5	2.4	-3.7	2.2	-1.2	1.0	10.3
% of Gait @ Max Dorsi-	36.6	6.7	37.1	2.8	0.5	0.0	39.8
Max Plantarflexion (mm)	-6.4	0.3	-21.0	1.0	-14.6	1.0	-19.3
% of Gait @ Max Plantar-	66.4	7.1	66.9	2.0	0.6	0.0	64.6
Range of Motion (mm)	3.9	2.5	17.1	2.8	13.2	1.0	29.6
Peak Moment (Nm)	31.8	4.1	17.4	2.1	-14.5	1.0	30.2
% of Gait @ Peak Moment	64.9	4.8	51.3	5.8	-13.7	1.0	42.1
Peak Power Out	15.0	3.1	16.3	3.6	1.3	0.0	22.4
% of Gait @ Peak Power	61.2	6.8	56.3	3.1	-4.9	1.0	49.6
Power Amplification (ratio)	0.7	0.2	1.5	0.2	0.8	1.0	1.9

TABLE IV

SUBJECT 3 KEY METRICS FOR OVER-GROUND DATA

	pre	(+/-) Std Dev	post	(+/-) Std Dev	Delta	Ttest	Typ Values
pace (steps/min)	34.9	1.7	37.2	1.8	2.3	1.0	33.1
Max Dorsiflexion (mm)	-0.4	2.8	0.1	2.8	0.5	0.0	10.3
% Gait @ Max Dorsi-	45.8	3.7	44.0	2.4	-1.8	1.0	39.8
Max Plantarflexion (mm)	-16.0	0.3	-20.4	1.3	-4.4	1.0	-19.3
% of Gait @ Max Plantar-	66.7	3.9	66.0	3.7	-0.7	0.0	64.6
Range of Motion (mm)	15.6	2.9	20.6	2.4	5.0	1.0	29.6
Peak Moment (Nm)	20.8	4.5	19.1	4.3	-1.6	1.0	30.2
% of Gait @ Peak Moment	52.7	5.0	48.1	2.8	-4.6	1.0	42.1
Peak Power Out (W)	19.0	6.5	17.2	5.7	-1.8	0.0	22.4
% of Gait @ Peak Power	55.4	2.6	52.6	2.9	-2.7	1.0	49.6
Power Amplification ratio	1.4	0.2	1.4	0.2	0.0	0.0	1.9

TABLE V

SUBJECT 3 KEY METRICS FOR TREADMILL DATA

	pre	(+/-) Std	post	(+/-) Std	Delta	Ttest	Typ PAFO Values
pace in steps/min	29.4	1.4	45.6	1.8	16.2	1.0	33.1
Max Dorsiflexion (mm)	6.1	2.8	11.5	2.0	5.4	1.0	10.3
% of Gait @ Max Dorsi-	49.4	2.2	43.4	1.5	-6.0	1.0	39.8
Max Plantarflexion (mm)	-14.7	1.4	-19.2	2.0	-4.5	1.0	-19.3
% of Gait @ Max Plantar-	66.1	2.0	67.4	3.0	1.3	1.0	64.6
Range of Motion (mm)	20.8	3.7	30.7	3.0	10.0	1.0	29.6
Peak Moment (Nm)	29.4	5.1	40.4	3.8	10.9	1.0	30.2
% of Gait @ Peak Moment	51.1	2.3	44.7	1.6	-6.4	1.0	42.1
Peak Power Out	26.6	7.0	50.2	10.6	23.6	1.0	22.4
% of Gait @ Peak Power	54.5	2.3	51.4	4.0	-3.1	1.0	49.6
Power Amplification (ratio)	2.0	0.3	1.5	0.2	-0.5	1.0	1.9

the treadmill, every key metric trended toward able bodied typical values, suggesting that the subject was able to adapt his gait to the robot. It is expected that the over ground data would not trend toward "typical values" as rapidly.

D. Over ground Walking Motion Capture Results - Subjects 1 and 3

The results from motion capture data for subject 1 show that there was a slight increase in speed of 0.03 m/s between the pre- and post-intervention testing. This increase was the result of a 9 cm increase in stride length and a 2.7 steps/min decrease in cadence. Further analysis of the stride length indicates that the right step length (i.e., right foot swing and left foot support) increased 1.8 cm and the left step length increased 7.2 cm. It should also be noted that during the first training session, the participant was able to walk for about 6 minutes at a speed of 0.26 m/s. During the final training session, the participant was able to walk for 18 minutes at a speed of 0.40 m/s.

For the left affected side, the motion capture data showed a clear separation between the pre- and post-intervention curves for the knee sagittal plane angles. These results are that knee extension went from 14 degrees pre-intervention to 3 degrees during post-intervention. In addition, knee flexion during swing went from 4 degrees to 17 degrees during pre- and post-testing sessions. Both of these results moved the participants gait pattern closer to that of a typical pattern.

For subject 3, motion capture data recorded the unassisted gait speed for over ground walking. The subject wore his traditional AFO during these recording sessions. Over ground walking results without the PAFO, but with the subjects personal AFO showed improvements in the 6 minute walk test, but no statistical change in natural, freely chosen, gait speed. There is no statistical difference in gait speed between the 8 trials pre-intervention and the 8 trials post-intervention, as proven by a two tailed t-test. On separate pre- and post-intervention days, 6 minute walk data were collected. This is a functional test where the subject walks continuously for 6 minutes and the total distance is recorded. There are only two data points on this test, so a measure of variability is impossible to obtain. The speed data determined by the motion capture system may suggest that the increased distance traveled post-intervention during the 6 minute walk test is within the variability, and not significant. However, another possibility is that the subject's average speed was increased from a gain in endurance, allowing him to cover more distance in a given time.

TABLE VI

MOTION CAPTURE SPEED DATA AND 6 MINUTE WALK DATA FOR SUBJECT 3

	Pre Intervention	Post Intervention
Gait Speed (cm/sec):		
mean	76.9	76.3
Std Dev	6.6	5.6
max	84	81
min	67	64
replicates	8	8
6 minute Walk (m):	317.7	394.1

V. CONCLUSIONS AND FUTURE WORK

In conclusion, all subjects had some positive changes in their key gait variables while using the PAFO. These changes were more dramatic while harnessed and using a treadmill. Over ground robot data suggests that positive changes in gait variables do occur, but at a slower rate than while on the treadmill. Subject 3 was able to adapt his gait to the robot very effectively while on the treadmill. His data stands out from subjects 1 and 2 primarily because of the custom fit robot. Comfort, stability, and robustness proved to be critical design parameters for developing a gait therapy robot capable of collecting repeatable data with low variability. It is not yet clear how well the positive changes seen while using the PAFO carry over to unassisted gait. Motion capture data showed that subject 3 has no significant change in natural walking speed. However, these data did show improvements in knee range of motion for subject 1, and the 6 minute walk data showed an increase in distance walked for both subjects 1 and 3. These positive results provide strong support for future work and the data collected in this study will aid in determining the required number of subjects for a clinical trial. This clinical trial will include a placebo therapy to distinctly determine the effects of robotic gait therapy on over ground unassisted gait.

VI. ACKNOWLEDGMENTS

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