Robot Assisted Gait Training With Active Leg Exoskeleton (ALEX)

Sai K. Banala, Seok Hun Kim, Sunil K. Agrawal, and John P. Scholz

***Abstract*—Gait training of stroke survivors is crucial to facilitate neuromuscular plasticity needed for improvements in functional walking ability. Robot assisted gait training (RAGT) was developed for stroke survivors using active leg exoskeleton (ALEX) and a force-field controller, which uses assist-as-needed paradigm for rehabilitation. In this paradigm undesirable gait motion is resisted and assistance is provided towards desired motion. The force-field controller achieves this paradigm by effectively applying forces at the ankle of the subject through actuators on the hip and knee joints. Two stroke survivors participated in a 15-session gait training study each with ALEX. The results show that by the end of the training the gait pattern of the patients improved and became closer to a healthy subject's gait pattern. Improvement is seen as an increase in the size of the patients' gait pattern, increased knee and ankle joint excursions and increase in their walking speeds on the treadmill.**

***Index Terms*—Force-field control, gait rehabilitation, rehabilitation robotics.**

I. Introduction

PROPER application of robotics has a potential advantage over therapy provided by human beings in terms of precision and repeatability. Robots are especially well suited in application areas where well controlled physical motion and force is required. Robotics is, therefore, potentially suitable for rehabilitation in physical therapy, where training to regain lost functional abilities plays a major role. Some of the advantages that robotic rehabilitation has over conventional manual rehabilitation are: 1) it may reduce the physical burden on clinical staff; 2) interaction forces and torques, measured with various sensors, can quantitatively assess the level of motor recovery; 3) robotics can help in delivering controlled repetitive training at a reasonable cost.

Loss of motor control can happen due to many medical conditions. Neurological injury, such as hemiparesis from stroke, may result in significant muscle weakness and impairment in motor control. Such patients often have substantial limitations in controlling movement, resulting in them losing ability to perform daily tasks. According to American Heart Association (2007), there are about 700 000 incidents of stroke every year [1]. Out of these, about 50% of the stroke survivors become completely or partially dependent. Except for severe cases, stroke survivors frequently have the ability to walk. But due to the impairment in motor control they develop compensatory strategies. These compensatory strategies may result in abnormal gait patterns after a stroke which are significantly related to dysfunction of muscle [2].

One of the treatment options for a stroke survivor is rehabilitation involving physical therapy. The goal of physical therapy is to help survivors regain the use of impaired limbs. The most important element of physical rehabilitation is retraining motor coordination by performing well-focused and carefully-directed repetitive practice [3]. Robotic rehabilitation could deliver such training to the patient by providing controlled assistance.

Different types of orthotic devices have been developed to improve gait rehabilitation in people with neurological disorders. Early orthotic devices developed for this purpose merely moved the leg of a stroke survivor or spinal cord injury patient in a fixed repetitive pattern. In later studies, different strategies were developed to elicit greater voluntary participation of the patient in the rehabilitation process, as the latter method has been deemed to be potentially more effective [4], [5].

One recent gait training study [6] conducted using Lokomat with 30 acute stroke survivors showed that after four weeks of therapy, the patients who received therapy with Lokomat (Lokomat group) had a significantly longer stance phase on the paretic leg when walking on the floor when compared to the subjects who received conventional physiotherapy (control group). The Lokomat group also showed increased muscle mass and reduced fat mass when compared to the control group. There was no significant difference between groups in gain of functional scores and gait parameters like walking speed, cadence, and stride duration. The study concludes that Lokomat training is a promising intervention for gait rehabilitation when compared to the conventional physiotherapy. However, the lack of a significant improvement of functional scores or gait parameters over standard gait training raises questions about the ultimate value of this approach.

Another gait training study [7] was conducted using Lokomat with 16 acute stroke patients for nine weeks, mostly within three months of onset. In this study, the patients were divided into two groups: ABA or BAB (A = three weeks of Lokomat training, B = three weeks of conventional physical therapy). This study concludes that automated gait training is more effective when compared to conventional physical therapy in improving walking on seven scales of function including speed,

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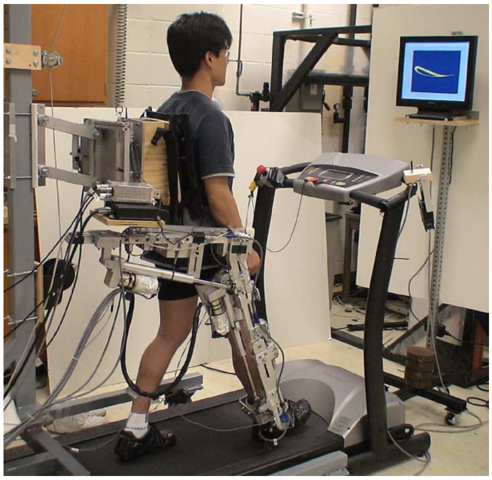


Fig. 1. Experimental setup with ALEX on the right leg of a subject walking on a treadmill. The computer display in front of the subject provides visual feedback of the gait trajectory.

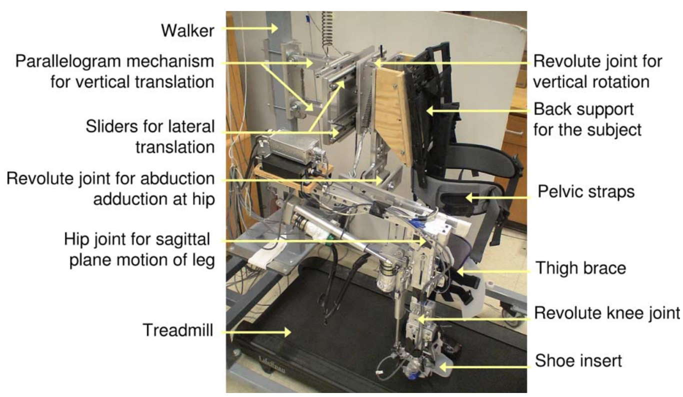


Fig. 2. Powered leg orthosis, its major components and all the DOFs are labeled.

endurance, muscle strength and tone. Studies using robot assisted gait training with chronic stroke survivors were not found in the literature. In this paper, a motorized orthosis for gait rehabilitation called ALEX (active leg exoskeleton) [8] is briefly described and a preliminary gait training study conducted with two chronic stroke survivors is described in detail.

II. Orthosis Design and Control

ALEX is a motorized orthosis shown in the Fig. 1, its components are labeled in the Fig. 2. The details of the device are described in [8]. The device is supported by a walker and the orthosis has several degrees-of-freedom (DOF) with respect to the walker. The overall setup has five main components.

1) Walker, which supports the weight of the device.
2) The trunk of the orthosis, which is connected to a walker and has three DOFs. These DOFs are vertical and lateral translations and rotation about vertical axis. The human trunk is secured to the orthosis with a hip brace. The human subject is allowed to lean forward in the hip brace.
3) Thigh segment of the orthosis has two DOFs with respect to trunk of the orthosis, one in sagittal plane and the other for abduction-adduction motion. The thigh segment is telescopic and can be adjusted to match the thigh length of a human subject.
4) The shank segment of the orthosis has one DOF with respect to the thigh segment. The shank segment, like the thigh segment, is also telescopic.
5) Foot segment, which is a shoe insert, is attached to the shank of the leg with one DOF ankle joint (plantar/dorsiflexion). The foot segment also allows limited inversion-eversion motion at the ankle due to its structurally flexible design. For controller the foot is considered as a point mass, therefore the ankle joint position is used as foot position.

All above DOFs were found to be the minimal number essential for achieving natural walking motion of a subject. Fig. 2 shows a photograph of the device with the DOFs labeled. The hip joint in the sagittal plane and the knee joint are actuated using linear actuators. These motors have encoders built into them, which are used to compute the joint angles. All the other DOFs are passively held by springs. Ankle joint angle is measured by using an encoder directly mounted at device ankle on foot-piece assembly. These motors can generate about 50-Nm peak torques at device knee and hip joints. The physical interface between the orthosis and the dummy/human leg is through two force-torque sensors, one mounted between thigh segments of the orthosis and the leg, the other mounted between shank segments of the orthosis and the foot brace on the human leg.

A force-field controller was developed which applies tangential and normal forces at the ankle of the subject. Such force-field controllers have been used in upper extremity rehabilitation [9]. The controller developed for ALEX applies a force-field at the ankle of the subject. Even though the linear actuators are mounted at the hip and knee of the orthosis, the torques generated at those joints simulate the forces applied at the ankle. The tangential forces help move the ankle of the subject along the trajectory and normal forces generate forces to simulate virtual-walls around the desired ankle trajectory in the plane containing the human thigh and shank. All the parameters of this controller can be changed during rehabilitation. Equation (1) gives the equation to the normal force, which is used to generate the virtual walls:

$$\mathbf{F}_n = \begin{cases} K_n \left(\frac{|d|-D_0}{D_n}\right)^2 \hat{\mathbf{n}}, & \text{if } |d| > D_0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where d is the distance from the ankle (point $\mathbf{P}$ in Fig. 3) to the nearest point on the desired ankle trajectory (point $\mathbf{N}$ in Fig. 3), D_0 is defined as the tunnel width, D_n is a constant with length units which is used to change the shape of the normal force $\mathbf{F}_n$ versus d curve. K_n is a constant with force units, which can be considered as a stiffness parameter. And $\hat{\mathbf{n}}$ is a unit vector pointing from point $\mathbf{P}$ to $\mathbf{N}$ (Fig. 3). This nonlinear parabolic normal force profile works like a stiffening nonlinear spring in helping to guide the ankle of a subject along the desired ankle trajectory.

The tangential force is defined as

$$\mathbf{F}_t = \begin{cases} K_{Ft} \left(1 - \frac{d}{D_t}\right) \hat{\mathbf{t}}, & \text{if } \frac{d}{D_t} < 1 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

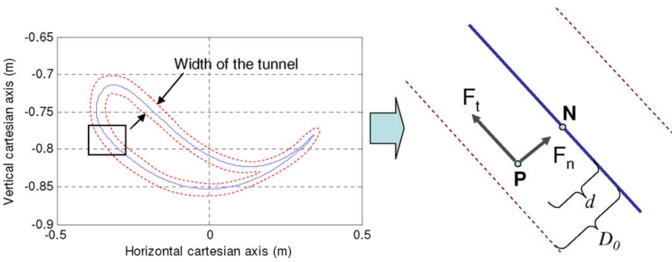


Fig. 3. Cartesian plot of the ankle in the trunk reference frame, origin set at the hip joint. The solid line (in blue) is the desired trajectory of the ankle and the dashed lines (in red) are the virtual walls. d is the shortest distance from point P to the trajectory.

where K_{Ft} and D_t are constants. K_{Ft} is used to change the maximum magnitude of the tangential force. During the experiment the value of K_{Ft} was chosen to be less than or equal to 10 N. $\mathbf{F}_t$ is maximum along the desired path (where $d = 0$), its magnitude decreases linearly and becomes zero at a distance of D_t from the desired ankle path. Note that the tangential force ramps down as the distance d increases, this is to apply tangential force only when the leg is closer to the desired ankle path. The tangential force is necessary to help the subject move his ankle along the desired path, the magnitude of this force can be changed during experiment by changing K_{Ft}. The damping force is given by $\mathbf{F}_d = -K_d\dot{\mathbf{x}}$, Where K_d is a constant and $\dot{\mathbf{x}}$ is the linear velocity of the ankle. The total force on the ankle is given by the vector sum $\mathbf{F} = \mathbf{F}_t + \mathbf{F}_n + \mathbf{F}_d$.

The force-field controller helps a stroke survivor during rehabilitation by using assist-as-needed paradigm. Maximum virtual wall constraints were applied during initial part of the training. It is worth pointing out that the optimal sequence of constraint magnitude to achieve training is itself a scientific question, which is under study. That is, the guidance provided by the normal forces at the ankle generate a very narrow virtual wall like forces (Fig. 3). The tangential force that assists the patient along the path is kept to minimum necessary to assist the patient to make the transition from terminal stance or toe-off to initial swing, this is done by changing K_{Ft}. This kind of maximum constraint of the virtual path applied during the initial part of the training provides proprioceptive feedback to the patient. As the patient's performance improves, this tangential force is further reduced to a very small value.

During the training, the subject is shown his ankle trajectory along with a template of desired ankle trajectory in real time, on a video display placed in front of the subject. The subject is asked to track the template as closely as possible. As the gait training progresses, the amount of assistance both in tangential assistance force and virtual wall guidance is reduced. However, because the visual guidance (or visual feedback) is still being given to the subject to track the template, the subject needs to use more voluntary effort to track the template. As the amount of assistance is gradually reduced, the subject needs to gradually increase voluntary participation in the training process. This training approach is based on previous studies that indicated the efficacy of robotic gait training with various trajectories [10]–[12], as well as the importance of subjects' voluntary participation to enhance gait training [13]–[15] and learning in general [16], [17]. In the next section, gait training study with two stroke patients using ALEX is described in detail.

III. Training Procedure

Two stroke survivors volunteered to participate in 15 sessions of training over a six-week period using robotic assisted gait training (RAGT). Both were chronic, having suffered a single-sided stroke to the middle cerebral artery territory of the left brain. Subject 1 was a 72 year old male who suffered his stroke 3.5 years ago. He was 1.87 m in height and 97.1 kg in weight. Subject 2 was a 47-year-old male who suffered his stroke 3.2 years earlier. He weighed 79.4 kg and was 1.80 m in height. The Berg Balance Score of each was 49/56 and 54/56 at the initial evaluation. The dynamic gait index (DGI) of subject 1 was 13/24 at the preassessment evaluation. Subject 2 had a DGI of 20/24 at the beginning of the training.

The goal of this gait training study is to help patients become more capable community-based ambulators. To do this, the training attempts to shape the patients' gait towards healthy subjects' gait pattern. The gait training paradigm is shown in Fig. 4. On each training day, the patient undergoes gait training in the treadmill for up to 3–3.5 h including setup and rest periods. Evaluation tests were conducted during the training, after first, second and last five-day blocks of training. Between each training period, the patients had 1.5 weeks of break. During this break, the patients were encouraged to practice their walking by going for a walk daily and carried out daily activities normally. No special training was given.

Each stroke survivor received both force-field constraints of the ankle path and intermittent visual guidance in the form of their ankle path in comparison to a prescribed path (template), which was based on that of a healthy control subject of similar stature. The continuous visual guidance was, however, provided for subject 1 until day 2 of training due to his difficulty in matching the template when visual guidance was turned off. During the initial 2 min of a training block, the visual feedback was turned on to provide the patient with explicit information with which he could correct his foot trajectory to match the prescribed trajectory. Then the visual guidance was turned off to prevent the patient from becoming dependent on visual guidance, although there remained proprioceptive guidance that was less directly linked to performance. The visual feedback was then reintroduced and removed again at 2-min intervals to provide the patient with explicit feedback about his errors. The interval for switching the visual feedback on and off was determined by trial and error.

On the first evaluation test (before the gait training), the patient's baseline gait pattern is recorded in ALEX. During this test, visual guidance is not shown and force-field is not applied. A prescribed ankle trajectory (template) is used for both force-field control and visual guidance. This template is constructed based on the patient's pretraining gait and a healthy control subject's gait, whose dimensions, primarily thigh and shank lengths, match closely with the stroke survivor. To obtain the healthy control subject's gait data, two healthy adults were tested on the treadmill at different speeds in a single session in ALEX, but without applied force-field controller. These

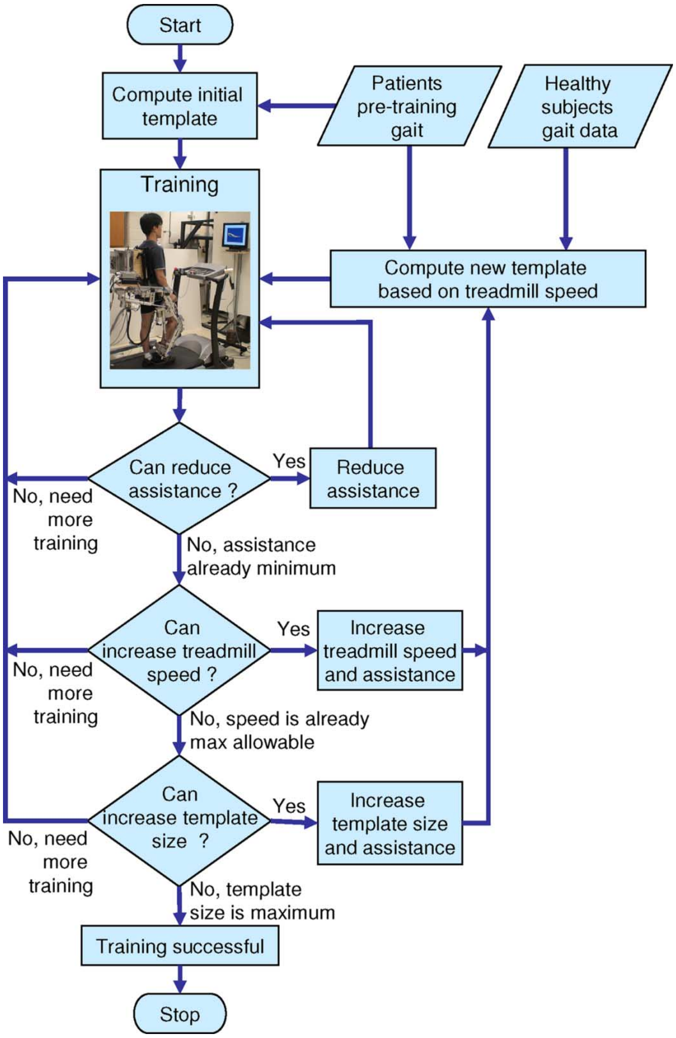


Fig. 4. Training paradigm used for stroke patients. By increasing the template size, we mean that the template size is made to be a step closer towards healthy subject's gait pattern, by changing the parameter η in (3).

data were used to determine the prescribed "ideal" target trajectory (template) for the gait training of the stroke survivors. The healthy control range of walking speeds that were obtained overlapped with and extended beyond the typical speeds of walking of the stroke survivors. Thus, the trajectory templates used were speed dependent.

Initially, the gait training starts with a template close to the patient's pretraining gait. As the training progresses (across the 15 days of training) and the stroke patient gets better at tracking the template, the difficulty is gradually increased by reducing the amount of assistance, increasing the treadmill speed, or stepping up the size of the template towards the healthy subject's gait (Fig. 4). The desired gait pattern (template) used in visual guidance and in the force-field controller was obtained by scaling each patient's pretraining gait pattern with the corresponding healthy subjects recoded gait data. For example, let the patient's pretraining hip and knee pretraining joint angles be θ_{ph} and θ_{pk} respectively. Let the healthy subjects recorded gait pattern be $\theta_{sh}(v)$ and $\theta_{sk}(v)$, where v is the treadmill speed used for that set of hip and knee joint angles. To obtain the template as hip-versus-knee for gait training (θ_h, θ_k) at treadmill speed of

TABLE I

DAILY RAGT PROTOCOL FOR A PARTICIPANT RECEIVING VISUAL FEEDBACK DURING TRAINING IS SHOWN. TWO WALL WIDTHS (D_0): NARROW (1 CM; NW: NARROW WIDTH) AND MEDIUM (2 CM; MW: MEDIUM WIDTH) AND TWO STIFFNESS COEFFICIENTS (K_n): HIGH (0.760 N; HS: HIGH STIFFNESS) AND LOW (0.125 N; LS: LOW STIFFNESS) ARE ALTERNATED DURING THE SESSION. (D_n WAS CHOSEN TO BE 0.1 CM)

Daily RAGT protocol			
Training/ Test Bout	**Time (min)**	**Force Field Constraint**	**Visual Guidance**
Adaptation	5	none	off
Baseline test	3	none	off
Pre-test	3	none	on
Training 1	5	NW-HS	on/off
Training 2	5	NW-HS	on/off
Training 3	5	NW-LS	on/off
Training 4	5	NW-LS	on/off
Mid-test	3	none	on
Training 5	5	MW-HS	on/off
Training 6	5	MW-HS	on/off
Training 7	5	MW-LS	on/off
Training 8	5	MW-LS	on/off
Post-test	3	none	on
Follow-up test	3	none	off

v, scaled by $\eta\%$ towards the healthy subject's gait pattern, the following weighted average was used:

$$\theta_h = \frac{[(100-\eta)\theta_{ph} + \eta\theta_{sh}(v)]}{100}$$
$$\theta_k = \frac{[(100-\eta)\theta_{pk} + \eta\theta_{sk}(v)]}{100}. \quad (3)$$

Thus, for $\eta = 0\%$, we get the patient's pretraining gait pattern. For $\eta = 100\%$, we get the healthy subject's gait pattern at treadmill speed of v. For other values of η we get a scaled gait pattern. By increasing η, the template becomes more challenging to track during gait training. This weighted average of the trajectories was done such that the heel-strike and toe-off events match and the points in between were interpolated accordingly. Finally the template reflecting hip versus knee is converted to a ankle trajectory template using the patient's thigh and shank lengths.

As explained in previous section, the force-field controller generates virtual, elastic tunnel walls that provide spring-like constraints for the prescribed ankle path. The initial ankle path was maximally constrained with a narrow virtual tunnel width and high wall stiffness to approximate the desired trajectory. With practice, the constraints were gradually reduced across the training bouts, as illustrated in Table I. Subjects were instructed to try to keep their actual ankle path as close to the prescribed path (template) as possible.

As the training progresses, the amount of assistance available to the subject is reduced, but it was done only when the patient was able to perform well at a given amount of assistance. The

TABLE II
INFORMATION OF STROKE SURVIVORS PARTICIPATED IN THE GAIT TRAINING STUDY

Parameter	Units	Stroke Survivor S1	Stroke Survivor S2
Age	years	72	47
Time post stroke	years	3.5	3.2
Body weight	kg	96.2	80.3
Height	cm	186.7	180.3
Thigh length	cm	42.0	41.5
Shank length	cm	46.2	42.5
Tolerable treadmill speed:			
First day of training	miles/hr	1.0	1.4
Last day of training	miles/hr	1.6	1.9
Preferred treadmill speed:			
Before training	miles/hr	0.9	1.3

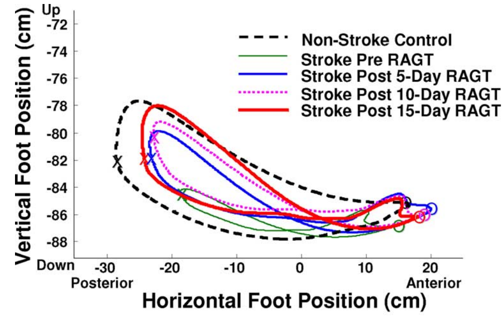
phrase "assist-as-needed" is used in the paper to describe the force-field controller, as even though the amount of assistance available to the patient is specified by the therapist, the actual amount of assistance being used by the subject depends on how he is performing. If the subject is performing well and was able to track his desirable gait pattern, the amount of guidance due to the normal force reduces. If the subject does not track the desired trajectory well, the magnitude of normal forces will increase to provide more guidance forces.

IV. RESULTS AND DISCUSSION

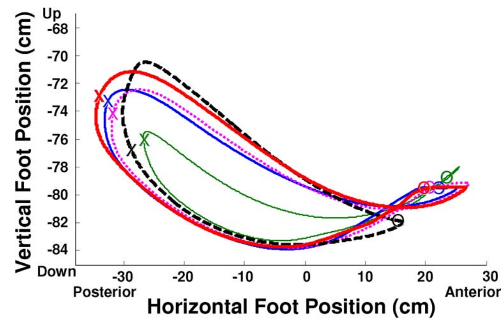
The two stroke survivors showed encouraging improvements in their walking ability after three five-day training sessions. Improvements were reflected by an increase in their tolerable treadmill walking speeds from 1.0 mph at the first training session to 1.6 mph at the end of training (subject 1) and from 1.4 mph to 1.9 mph (subject 2), see Table II. In addition, as noted, the size of the healthy subject's template was morphed downwards initially to a size that each stroke subject could match reasonably well, albeit with effort. Over the three five-day blocks of RAGT, both subjects showed significant improvements of their ability to match their healthy control's template. The template size (η) increased considerably, from 20% to 85% of the normal ankle path for the subject 1 and from 20% to 100% for the subject 2.

Fig. 5 shows the averaged ankle trajectories of the patients during evaluation trials, force-field control, and visual-feedback is off during evaluation. The figure indicates that the sagittal plane ankle trajectories of the subjects became much closer to that of the healthy control over 15 days of training. Please note that the ankle position was measured in a reference frame attached to the hip joint of the subject with the origin at the hip. The failure of the subject 1's stance phase (lower) portion of the depicted paths for each follow-up test to overlay each other was due to the subject having more or less flexion of the leg during the stance phase [Fig. 5(a)]. This was not an issue for the swing phase.

To compute the amount of retraining, the following measure is used: the area between swing phases of given test gait cycle and the healthy controls gait is computed. This area is shown in the Fig. 6(a). As this area gets smaller, it indicates that the adaptation to a healthy subject's gait pattern is getting better. This area between the actual ankle path and the template during the swing phase decreased from 158.6 cm^2 and 155.2 cm^2 at the baseline test to 99.7 cm^2 and 79.6 cm^2 after the first five-day training block, to 72.2 cm^2 and 78.6 cm^2 after the second five-day training block, and to 66.9 cm^2 and 63.9 cm^2 after the third five-day training block for subjects #1 and #2, respectively [Fig. 6(b)]. The bar graphs also show that substantial improvement occurred during first five days of training.

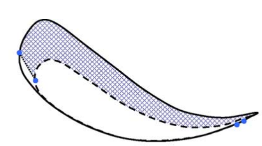


(a) Subject #1

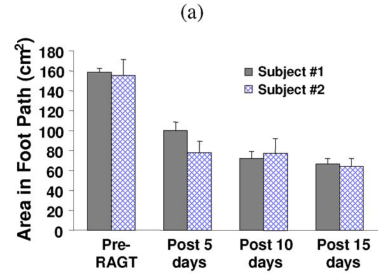


(b) Subject #2

Fig. 5. Ankle trajectories of stroke subject (a) 1 and (b) 2, all at their preferred speed at initial evaluation, i.e., 0.9 mph and 1.3 mph, respectively. Toe-off (X) and heel-strike (O) events were identified by foot switches placed to the sole of shoes. Please note that the ankle position was measured in a reference frame attached to the hip joint of the subject with the origin at the hip.

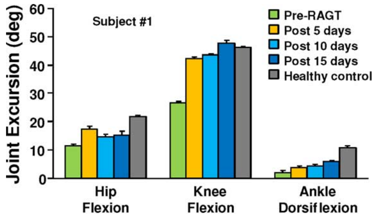


(a)

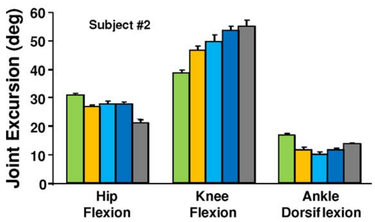


(b)

Fig. 6. Area between the actual ankle trajectory of each evaluation and the healthy control's template was computed from Fig. 5 for the swing phase only. (a) Shaded area is computed. (b) The area for both the subjects at different evaluation tests. The error bar stands for the standard error of the mean.



(a) Subject #1



(b) Subject #2

Fig. 7. Join excursions of stroke subject (a) 1 and (b) 2 during baseline treadmill walking (pre-RAGT), after the first five days of RAGT (post 5 days), after 10 days of RAGT (post 10 days), and after 15 days of RAGT (post 15 days), all at their preferred speed at initial evaluation, i.e., 0.9 mph and 1.3 mph, respectively.

In addition, joint excursions of the subjects' affected leg during the swing phase of treadmill walking increased progressively over 15 days of RAGT [Fig. 7 (a) and (b)]. In particular, the knee joint excursion into flexion increased remarkably from $25.3 \pm 1.5^\circ$ at the baseline test to $49.5 \pm 1.4^\circ$ after the third five-day training block for the subject 1 and from $17.3 \pm 1.9^\circ$ at the baseline test to $48.2 \pm 1.5^\circ$ after the third five-day training block for the subject 2. Noticeable increase of the ankle joint excursion was also found for both subjects, especially subject 2 (from $4.3 \pm 0.5^\circ$—before training to $15.3 \pm 1.1^\circ$—after 15 days of training).

Overall, the stroke survivors trained by a novel robotic training using visual guidance combined with force-field constraint showed improvement of their gait patterns. Previously reported robotic trainings moved the participant's limb passively through a fixed trajectory [6], [7], which may not motivate the participant to actively correct their abnormal gait pattern. However, by providing an elastic force-field tunnel, our approach encourages the participant to be involved in persistently correcting their walking towards a more normal gait pattern. Although the results of this current study are promising, it is not possible to draw definitive conclusions due to the limited number of subjects.

Of course, the ultimate test of the training's effectiveness is whether patients' over ground walking ability and community ambulation improve significantly. The answer to this question awaits more extensive studies that compare ALEX+force field control to more conventional gait training methods such as body-weight supported treadmill training. We are in the process of initiating such a study. However, both patients in the current report also showed notable improvements in their over ground walking ability (manuscript in review). Thus, the preliminary results are encouraging.

V. Conclusion

ALEX along with force-field controller were developed for gait rehabilitation of stroke survivors to help in retraining the gait pattern by using assist-as-needed approach which allows the patient to participate more actively in the retraining process compared to other currently available robotic training devices. Suitable training paradigm was developed and the training protocol was used for gait training study of two stroke survivors. The gait training study was conducted over 15 sessions for both the patients. The results show that the patients' gait patterns were substantially improved after the training. For subject 1 the ankle path area reduced by 57.8% and for subject 2 it was reduced by 58.8% towards the swing phase ankle trajectory of a healthy control subject of similar stature. This shows that by using ALEX with force-field controller for intensive gait retraining has the potential to provide significant benefits, even in chronic stroke survivors. Future work will need to evaluate the impact of ALEX plus force-field controller training on the community walking ability of patients as well as determine the best parameters for administering the training program on a daily basis. This work is currently underway.

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