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A Real-Time Auditory Feedback System for Retraining Gait

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Abstract—**Stroke is the third leading cause of death in the United States and the principal cause of major long-term disability, incurring substantial distress as well as medical cost. Abnormal and inefficient gait patterns are widespread in survivors of stroke, yet gait is a major determinant of independent living. It is not surprising, therefore, that improvement of walking function is the most commonly stated priority of the survivors. Although many such individuals achieve the goal of walking, the caliber of their walking performance often limits endurance and quality of life. The ultimate goal of the research presented here is to use real-time auditory feedback to retrain gait in patients with chronic stroke. The strategy is to convert the motion of the foot into an auditory signal, and then use this auditory signal as feedback to inform the subject of the existence as well as the magnitude of error during walking. The initial stage of the project is described in this paper. The design and implementation of the new feedback method for lower limb training is explained. The question of whether the patient is physically capable of handling such training is explored.**

I. Introduction

Stroke is the third leading cause of death in the United States [1]. Each year, approximately 800,000 people suffer a stroke, with the disease killing about 140,000. Once the acute phase, specifically the first six months, is completed, the outlook for survival improves. More than half of such patients are alive at seven years, resulting in 6 million survivors of stroke alive today. However, stroke is the principal cause of major long-term disability, with 75% of the survivors manifesting severe movement disability and 50% of the survivors dependent in activities of daily living. Many of the survivors make only minimal recovery even though motor and functional recovery can occur in spite of extensive neurological damage and advanced age [2]. The severity of unresolved motor deficits may have considerable impact on the physical, psychological, vocational, and socioeconomic conditions of the patient, and hence on personal, family, and community functions. Moreover, treatment incurs substantial medical costs. Acute rehabilitation services for in-patients cost upward of $1,200 per day.

A fundamental movement skill necessary for functional activities is locomotion, and compromised locomotion is a widespread motor deficit in the stroke population. The ultimate goal of the research presented in this paper is to use real-time auditory feedback to retrain gait in patients with chronic stroke, that is, patients who are at least six months post stroke. The strategy is to use error feedback during the locomotion task, where error is defined as the difference between the actual and desired performance, in this case the movement of the foot. The aim is to enhance motor recovery, i.e., to improve the biomechanical construction of the movement, and as a consequence to elicit functional changes, i.e., to effect improvement in activities of daily living such as initiation of gait, walking, turning maneuvers, ascending and descending stairs, and ingress and egress of vehicles.

A similar feedback strategy was used successfully by the authors to improve reaching in patients following stroke [3]. However, significant differences exist between the upper and lower extremities with regard to this type of training. Reaching is done with the patient in a seated position; it is characterized by continuous movement of the arm throughout the reach; arm movement takes place in the same workspace of the arm for each reach; and reaching involves movement of only one arm with the other arm stationary. Locomotion requires a translation of the whole body; it contains portions in which the foot is stationary; leg movement takes place in a different space for each step; and locomotion involves movement of both legs simultaneously. As a result, the feedback strategy for locomotion, while preserving the basic idea of the feedback strategy for reaching, required major changes. Furthermore, from the perspective of the patient, there was no issue of balance in reaching since the patient was seated, but locomotion introduces a serious concern as to whether the patient can attend to the feedback and simultaneously maintain balance.

The project described in this paper addresses the necessary initial stage of using real-time auditory feedback to improve gait. First, the design and implementation of the new feedback strategy appropriate for lower limb training is given. Second, the question of whether the patient is physically capable of handling such training is answered, ignoring at this stage whether it results in motoric improvement.

II. Background

The effectiveness of focused rehabilitation programs for patients with stroke has been demonstrated repeatedly [4]. Documentation of success of conventional therapies in restoring voluntary movements in patients with stroke has been limited [5]. In contrast, sensory feedback therapy has

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been utilized with greater success as a treatment intervention for patients with chronic stroke with postural and movement disorders [6]. Under normal conditions motor activities can be significantly altered in the presence of sensory signals conveying information concerning the error in performance, but in an impaired system the ability to translate error signals into modified performance may be affected. Recovery is aided by nonspecific factors, but substantial improvement will most likely require specific factors, i.e., regulated sensory feedback of the error within the context of a task, and the use of sensory substitution systems [7].

It was once thought that the process of recovery occurs only within the first six months following a stroke, and beyond that there is little that can be done to help the patient. Now there is mounting evidence that shows that this is not the case, and many clinicians now believe that proper rehabilitation can be effective years after the stroke [8].

III. Feedback System

Throughout this paper, the term “trajectory” will refer to the position or orientation of a body segment as a function of time. The term “path” will refer to a sequence of points traversed by a segment, and it is independent of time. A “stride” is the gait portion between a heel strike of one foot to the next heel strike of the same foot; “stride length” is the distance between the two heel strikes; a "stride trial" is a continuous sequence of strides. A stride for one foot is composed of a stance phase during which the foot is stationary and on the ground, immediately followed by a swing phase during which the foot is moving and in the air.

The feedback system operates by performing real-time conversion of the path of one foot during the swing phase into an auditory signal, and then using this auditory signal as feedback to inform the subject of the existence as well as the magnitude of error during a stride trial. Note that it is the error not the state that is fed back. Additionally, at the end of each stride trial, the subject is given an overall evaluation of the trial in the form of a visually presented number.

A. Hardware and Software

The hardware consists of two pressure switches for defining the beginning and end of the stance phase, a device for recording the trajectories of the leg segments, a mechanism for delivering auditory feedback in real time to the subject concerning the ongoing path of the foot, and a mechanism for delivering numerical visual feedback of the goodness of the completed path. All of these components are interfaced to a PC-compatible microcomputer.

One pressure switch was placed on the bottom of the shoe at the heel for defining the beginning of the stance phase and one on the bottom of the shoe at the toe for defining the end of the stance phase. Kinematic data acquisition was accomplished with the 3SPACE FASTRAK manufactured by Polhemus Navigation Sciences. This is a real-time, electromagnetic mechanism that provides the position and orientation, i.e., the six degrees of freedom, of a moving receiver relative to a fixed transmitter. Attaching the receiver to a rigid body allows the recording of the three translational (x, y, and z) and the three rotational (azimuth, elevation, and roll) coordinates of the body. Data acquisition rate is 60 Hz per signal for each receiver. Each receiver is about 2 cm^2 and weighs about 17 gm. One receiver was affixed to the top of the shoe at the tip, making available the exact location and orientation of the foot at each instant throughout the interval of motion. Note that this allows for the calculation of velocities and accelerations also. In future stages of the project, a second receiver will be placed on the thigh segment to enable the acquisition of the kinematic history of the entire leg complex. The receiver cables are 6 m long allowing the subject to ambulate for about 12 m. The microcomputer speaker was used to deliver auditory feedback in real time to the subject concerning the path of the foot. A 2100SB Series Displays from Vorne Industries, Inc. was used for delivering a single path-related number immediately following the locomotion that quantifies the locomotion as a whole.

Although the cable lengths permitted the subject to travel 12 m, the range of the FASTRAK was much more limited (the receiver detects the transmitter's magnetic field which decays with distance so the range depends on the distance between the receiver and the transmitter) and not sufficient to accommodate the desired number of strides. We therefore synchronized two FASTRAK transmitters so that, using only one set of receivers, the first transmitter covered the first half of the movement and the second transmitter covered the second half. This greatly increased the range for the signal and the number of strides from which data could be acquired. We did not encounter any problems with drift because the receiver is passive. In a previous study [9] we demonstrated by using the electromagnetic tracker system in tandem with a video motion analysis system that the transmitter's magnetic field was not affected by external sources.

The software is written in the C programming language. It consists of control, acquisition, auditory feedback, visual feedback, and calibration routines.

B. Normal Stride

Six subjects with normal walking as defined by routine examination of their gait were recruited. It was also required that they have no history of abnormal locomotor patterns. Subjects were males and females between the ages of 65 and 84. Each subject was tested on two occasions, called sessions. At each session, the subject performed eight stride trials, each trial consisting of six strides. All strides took place on a straightaway. The subject was instrumented with the pressure switches on the bottom of the right shoe, and a receiver on top of the right shoe. The right limb was chosen in order to be compatible with the patient population (see Section IV). A typical stride trial proceeded as follows. A gentle computer tone was emitted to signify that the subject should begin walking whenever he or she was ready. The subject performed the strides. A gentle computer tone was emitted at the end of the strides to signify the end of the trial. It was emphasized to the subjects that speed is not important, and that they should try to find their natural stride length and stride duration. Since each individual has a natural preferred stride length and duration, each session had practice trials for familiarization and to establish the subject's natural patterns. The middle four strides from each of the eight stride trials for Session 2 were used to construct a normal path region for the foot. The elimination of strides is because the first stride in each trial contains gait initiation anomalies and acceleration and the last stride deceleration, and previous work has shown that the first session in this type of study is marked by considerable variation within and between subjects [3].

C. *Feedback Design*

A normal path region was established for the toe portion of the foot, called the end effector, with the following algorithm. For each normal stride, consider the line, called the z-line, that joins the point on the ground from which the toe lifts at the beginning of the swing phase and the point in space where the toe is located when the heel strikes the ground at the end of the swing phase. Divide the z-line into a fixed number of segments of equal length. For each data point in the stride, project the point to the z-line to determine with which segment it is associated, and calculate the distances of the toe from the z-line in two orthogonal coordinates. For each z-line segment, calculate the means and standard deviations of the two distances over all strides and all subjects. Construct an ellipse with center at the means, and major and minor axes and angle of rotation determined by the variance and covariance of the set of distance pairs. This produces a fusiform region in space which is a volume through which the normal toe travels throughout the swing phase. An ellipse rather than a circle was used because the normal data revealed that the lateral variance of the foot is greater than the vertical variance, so the subject is allowed more leeway in the lateral direction.

A feedback strategy was then created to coax abnormal end effector paths to the normal profile. Auditory and visual feedback is administered at the time of the stride according to the following algorithm. Consider the z-line, this time based on a first point, i.e., the location of the toe at toe-off, that is pre-calibrated in the medial/lateral (ML) and anterior/posterior (AP) directions from the normal data, and a last point, i.e., the location of the toe at heel strike, that is pre-calibrated in the ML direction from the normal data and in the AP direction from passive stretch of the subject's leg at the beginning of the session. Divide the z-line into the same fixed number of segments of equal length. At each time interval, determine with which segment the toe is associated. For the auditory feedback, if the toe is within the associated ellipse no tone is emitted; if it is outside the ellipse a tone is emitted immediately with a frequency that increases over several standard deviations of the distances and remains at its maximum after that point. The auditory feedback is given in real time during the time interval of movement and is an on-line transmission of the error in the motor act. For the visual feedback, if the toe is within the associated ellipse a maximum value is accumulated; if it is outside the ellipse a value between half the maximum and 0 is accumulated that linearly decreases over several standard deviations of the distances and a 0 is recorded beyond that point. At the end of the strides, the accumulated value is transformed into a percentage of the total possible value for the strides and presented on the visual display. The final value is between 0 and 100 and, as with the auditory feedback, is based on how well the toe stayed in the normal path region. The visual feedback is given off-line after the movement has been completed, and conveys the adequacy of the response described as an error at the termination of the motor act. It is also a motivational impetus.

D. *Observations*

Several comments regarding the feedback system are worth emphasizing.

- The feedback is an auditory signal that increases in frequency the farther the actual motion deviates from normal. The salient features of the feedback are as follows.
  - It is presented to the subject in real time as the subject is walking so the subject is advised immediately of his or her performance.
  - It is an error signal, i.e., it is the difference between the subject's actual toe path and the desired toe path as given by the normal profile, and the magnitude of this difference is presented to the subject so he or she is apprised of the amount of error.
  - It is auditory which makes it simple to attend to and does not place any additional visual or semantic or tactile loads on the subject.
- Although the auditory feedback is given in real time, subjects can choose not to use it to alter the current stride, since that may jeopardize balance, but rather to use it to make corrections on subsequent strides.
- By means of the z-line, the feedback strategy fits the normal path region to the individual subject in order to account for the fact that different subjects have different stride lengths. It is also independent of time and velocity. The subject is trained to remain in the normal fusiform region but may traverse the region at his or her own pace without penalty.

IV. Patient Response

A small, informal study was done to determine if there were any insurmountable problems with administering this type of auditory feedback for gait training. Specifically, we sought to determine if there would be a balance issue and if the patient was capable of attending to the feedback signal during this type of movement task.

Eight patients with chronic stroke were recruited, all with a left hemisphere lesion meaning that the right limb was the affected limb. Inclusion criteria were that they demonstrate sensory thresholds, have no other neurological or muscular conditions, and exhibit moderate to severe range in motor scores. Exclusion criteria were inability to ambulate without an assistive device and certain stepping styles such as drop foot, since the system cannot handle these. Subjects were males and females between the ages of 65 and 84. Patients with left hemisphere lesions were chosen because they have less problem with memory, learning, attention, spatial orientation, and head-eye coordination than those with right hemisphere lesions, and thus the motor control component of the task can be better isolated. Assessment measures were done for active range of joint motion, joint position sense (e.g., imitate the monitor's leg position without looking at your leg), and motor scores (e.g., volitional movement in and independent of synergies). Gait distortions included unsteady initiation of gait, widened stance, abnormal stance duration, shuffling, swerving, difficulty turning.

Each patient was given three sessions, each session consisting of eight stride trials, and each stride trial consisting of six strides. All strides were on a straightaway. Instrumentation, computer tones to signify the start and end of a trial, practice trials, and instructions concerning natural stride length and duration were as for the normal population. At each session, the patient performed two stride trials without feedback, followed by four trials with feedback, followed by two trials without feedback. For the trials involving feedback, the auditory feedback was given throughout the six strides, and the patients were instructed to try to keep the auditory notes off or as low as possible throughout the strides by finding and staying in the correct path. The visual feedback was given at the end of the six strides to inform the subject of the overall result of the strides.

All patient sessions were conducted by two medical monitors. The patient wore a transfer/gait belt at all times, and one monitor walked beside the patient during all strides. There was no occasion for any of the patients when the monitor had to intervene to prevent a fall. At times, some patients used the monitor for balance or security. At the end of the final session, patients were debriefed. All stated they were comfortable with the system, understood what was expected of them, and would be willing to return for a full training protocol aimed at improving their gait. Thus, no inherent problems emerged in this testing of the feedback system.

Although no quantitative analysis was done on the patient gait data, some anecdotal impressions can be given. Patients did not seem to proceed at a slower pace to use the feedback. They did not make exploratory movements to find the path, presumably because that would require standing on one foot for a longer period of time and hence would disrupt balance. Instead, they appeared to approach the task in a way similar to that of the patients in the reaching study [3]. After several strides, they were able to internalize the movement that reduced the sound. They would then try to replicate that movement as a whole on subsequent strides.

V. Conclusion

The next stage of the research will be a pilot study to determine if the real-time auditory feedback described here is in fact effective in improving abnormal gait. Prior to this study, we will examine several possible alternatives.

Only the paretic limb was chosen for training, but it may prove easier for the patient to receive feedback for both limbs. There is no time during a walking stride when both feet are in swing so this will not lead to confusion. Feedback was given only during the swing phase because this is the only time there is movement of the foot and when corrections can be made. However, since the temporal ratio of stance to swing is also affected in the patient with chronic stroke, it may be necessary to include the stance phase in the training as well by signaling when the stance is terminated incorrectly. Also, we may take into account an individual's natural stride height as well as natural stride length.

The foot path was chosen for feedback based on results obtained by the authors for the arm. That study showed that when an affected hand [end effector] path alone is trained back to normal functioning, other biomechanical features of the arm [link system] such as shoulder abduction return to normal values as well. Nonetheless, points other than the toe [end effector] and also joint angles of the leg [link system] will be considered as candidates for feedback.

We will consider providing a positive feedback element in the form of praise and encouragement to ward off frustration when progress is slow. This will be measured, automated, and given at the time of the visual feedback

References

[1] American Heart Association. 2006. *Stroke Statistics*. Available: www.americanheart.org/presenter.jhtml?identifier=4725.

[2] M. L. Dombovy and P. Bach-y-Rita, "Clinical observations on recovery from stroke," *Adv. Neurol.*, vol. 47, pp. 265-276, 1988.

[3] R. A. Maulucci and R. H. Eckhouse, "Retraining reaching in chronic stroke with real-time auditory feedback," *NeuroRehabilitation*, vol. 16, pp. 171-182, 2001.

[4] T. Hoffmann, S. Bennett, K. McKenna, J. Green-Hill, A. McCluskey, and L. Tooth, "Interventions for stroke rehabilitation: analysis of the research contained in the OTseeker evidence database," *Top Stroke Rehabil.*, vol. 15(4), pp. 341-350, July-August 2008.

[5] R. A. States, Y. Salem, and E. Pappas, " Overground gait training for individuals with chronic stroke: a Cochrane systematic review," *J. Neurol. Phys. Ther.*, vol. 33(4), pp. 179-186, December 2009.

[6] J. J. Tate and C. E. Milner, "Real-time kinematic, temporospatial, and kinetic biofeedback during gait retraining in patients: a systematic review," *Phys. Ther.*, vol. 90(8), pp. 1123-1134, August 2010.

[7] R. Herman, "A therapeutic approach based on theories of motor control," *International Rehabilitation Medicine*, vol. 4, pp. 185-189, 1983.

[8] L. M. Homer, "Where rehab technology and expertise result in patients experiencing accelerated recovery," *M.D. News*.

[9] R. H. Eckhouse, M. A. Penny, and R. A. Maulucci, "A comparison of kinematic recording instruments," *J. Med. Syst.*, vol. 20(6), pp. 439-456, 1996.