Retraining reaching in chronic stroke with real-time auditory feedback

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Stroke is the third leading cause of death in the United States. The aim of the present study was to enhance the motor recovery of patients in the chronic stroke period by means of upper extremity trajectory modification through real-time auditory feedback. A system of hardware, software, and feedback algorithms was developed. Two groups of patients in the chronic stroke period were trained on the system, one with practice and feedback and one with practice alone. Twenty reach parameters were defined and analyzed for differences between the first and last training sessions, between adaptation and learning trials, and among three targets. This study demonstrated that modification of the reach trajectory can be accomplished during the chronic stroke period either with practice alone or through practice accompanied by auditory feedback. However, improved path performance requires auditory feedback training and cannot be achieved by practice alone.

Keywords: Stroke, reaching, arm trajectories, end effector path, real-time feedback, treatment

1. Introduction

A stroke is the sudden onset of a focal neurological deficit due to a presumed disturbance in the blood supply to the brain. Stroke is the third leading cause of death in the United States, affecting approximately 600,000 people each year and resulting in approximately 160,000 deaths. It is encouraging to note that more than 50% of patients who survive the acute phase are alive after seven years, with approximately 4 million survivors of stroke alive today. However, stroke continues to be the leading cause of major long-term disability. Seventy-five percent of survivors manifest severe residual movement disability while 30–60% are dependent in some aspects of activities of daily living [1]. Many survivors make only minimal recovery even though motor and functional recovery can occur in spite of extensive neurological damage and advanced age [4].

There are important economic and social implications of these statistics. Treatment can incur substantial medical costs, as well as utilize considerable resources in the form of rehabilitation time from therapists of various specialties. Moreover, persistent unresolved deficits may have a considerable negative impact on the physical, psychological, vocational, and social life of the patient, and by extension affect the family and the community.

Following a phase of post-stroke deterioration and a subsequent phase of motor stability, a motor recovery period ensues often within the first week [5]. In general, motor recovery is from proximal to distal and from mass-, patterned, undifferentiated movement to fine, isolated movement. The usual course of return of function in the upper extremity proceeds through several sequential stages: flaccidity with no or difficult to elicit stretch reflexes, spasticity in the antagonistic muscles, reflex stereotyped synergistic movement with the flexor synergy followed by the extensor synergy, volitional movements within the flexor-and extensor synergies, and volitional movements out-of-synergy with fractionated motor patterns and isolated joint motion [3]. Recovery in the upper extremity is most pronounced in the early months. By three months, 40% of limbs initially deemed non-functional attain a moderate to mild state, 75% initially moderate achieve a mild state, and 75% initially mild are unimpaired. It is also noteworthy that at six months, measures of activities of daily living skills may produce perfect or near-perfect scores; whereas motor indices may continue to imply substantial impairment [5]. Many investigators assert...
that clinical studies assessing the efficacy of a specific treatment on the recovery of motor function should be conducted on patients who are at least six months post-stroke, i.e., in the chronic stroke period. Presumably, such patients have attained a plateau in their recovery, and any further improvement would not be ascribed to the spontaneous recovery that occurs during the first six months, i.e., the acute period.

Augmented sensory feedback therapy has been used as a treatment modality for patients in the chronic stroke period, as well as for patients with varied other disabilities [2,7]. The rationale for such treatment lies in the observation that the central nervous system exhibits remarkable plasticity of function, leading to two hypotheses [9]. First, under normal conditions, motor activities can be significantly altered in the presence of sensory signals conveying information concerning the error in performance. However, in an impaired system the ability to translate error signals into modified performance may be affected. Second, recovery is aided by nonspecific factors, i.e., random sensory experiences encountered during daily life do contribute to improved performance, but this is insufficient. 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. Sensory feedback may employ one or both of two means for delivering error information. These are described as knowledge of performance and knowledge of results [15]. Knowledge of performance refers to an on-line transmission of the error in the motor act given during the act, meaning that the patient is aware of the error at the time that it is produced and allowing the patient to make corrections during the current execution of the task. Knowledge of results refers to the adequacy of the response given as an error at the termination of the motor act, meaning that the patient is notified of the error after completing the current execution of the task and can use the information to perform better on the next execution of the task.

Reaching as an instance of guided limb motion is a fundamental movement skill necessary for many activities of daily living. Upper extremity reaching to a target is a task that has been studied extensively in the impaired and unimpaired limb [8,14]. Many of these studies have concentrated on task analysis by addressing the initiation, interior, and termination of the movement, as well as the spatial and temporal elements, joint angle constructions, and EMG profiles that define the task.

The aim of the present study was to enhance the motor recovery of patients in the chronic stroke period by means of upper extremity trajectory modification through auditory feedback. A test arena was constructed to accommodate reaching movements for a population with right hemiparetic stroke. Instrumentation was designed and software was implemented for delivering auditory feedback based on kinematic signal characteristics. A cohort of unimpaired subjects was examined with the system, without employing the feedback capability, to determine normal trajectories for this type of reach. An error feedback strategy was developed, intended to coax the impaired trajectory toward the established normal trajectory. The system was tested on two groups of patients in the chronic stroke period, one with and one without feedback, to investigate whether the system can induce improvement of impaired trajectories and whether such improvement in reach is attributable to feedback or merely to the result of practice.

2. Methods

Subjects made reaching movements to three targets located in the workspace of the arm, using specially designed structures, hardware, and software. Three groups of subjects participated: unimpaired, normal practice, and feedback groups. The following definitions will be used. A trajectory refers to the translational and rotational motion of the arm segments through space during a task. Trajectory modification refers to changes made by the subject to the usual execution of that motion as a result of training. Adaptation denotes trajectory modification that takes place immediately after training, i.e., at the end of the training session; learning denotes trajectory modification that takes place after time training, i.e., the retention and use of trajectory modification from one session to another.

2.1. Hardware

The hardware system consists of a touchplate for defining the onset of arm movement, targets for defining the endpoint and the termination of the arm movement, and a device for recording the trajectories of the arm segments. All of these components were interfaced to a PC-compatible microcomputer for automated experiment control and data acquisition.

The touchplate consists of a copper square that is attached to the armrest of the chair in which the subject is seated. By means of specially developed circuitry, the plate is capable of sensing when the arm is resting on it. Thus, the tin with the plate, that ment, is detected a back wooden chair, the proximal port is adjustable.

A target contains square, allowing the subject to move a target with 4.5 contact paper with center. It is attached to a particular stick which is clamp and feet make the stick can be adjusted to be placed. The structure can be placed together, the interval over which the three targets can be used with the exception that is mounted on the left angle with the right shoulder.

Kinematic data a 3SPACE ISOTRACK navigation system, which measures distance in space, i.e., sensor relative to the rigid body coordinate system, was placed on the upper arm (x, y, z, elevation, and roll) was fixed to the target location and throughout the test. The sensor did not enable the acquisition of the entire arm composed of the synergies that contribute to arm trajectories. The sensor was interfaced to a PC-compatible microcomputer for automated experiment control and data acquisition.
A test arena was set up to study movements for stroke. Instruments implemented for ten kinematically impaired subjects with employing the normal trajectory tracking strategy was called trajectory tracking. The system was designed to chronic stroke patients, to investigate the improvement in their performance in tasks relevant to the results presented.

Three targets were used with specially designed software. Three 90-making definitions for the middle target, the horizontal bar, and the vertical bar refer to changes in the orientation of that motion denoting either immediately after session, learning takes place some distance away.

A target plate for targets with defined trajectory trajectories of the wave intensity automated was square that is aligned with the subject's hand. The arm is resting on it. Thus, the time at which the arm breaks contact with the plate, that is, the time of initiation of movement, is detected and recorded. The chair is a straight back wooden chair. The armrest is short, holding just the proximal portion of the forearm, and is vertically adjustable.

A target contains a similar touch sensitive copper square, allowing target contact which signifies the termination of movement to be detected and recorded. The target has 4.5 cm sides and is covered with black contact paper with a 1.5 cm radius circle cut out of its center. It is attached to a rectangular block of wood which also contains a small light above the target that can be activated to indicate which target is to be touched during a particular trial. The block is mounted on a stick which is clamped in a horizontal bar. Side panels and base make this a self-supporting structure. The stick can be adjusted to any lateral position, the bar can be adjusted to any vertical position, and the entire structure can be placed at any distance from the subject. Together, the touchplate and target serve to define the interval over which the trajectory is assessed and enable the movement time to be calculated. There are three target plates clamped in the bar. They are identical with the exception that the middle target is mounted perpendicularly to the stick, whereas the blocks for the left and right targets are mounted at 20 degree angles facing them toward the middle.

Kinematic data acquisition was accomplished with a 3SPACE ISOTRAC system, manufactured by Polhemus Navigation Sciences. This is a real-time, electromagnetic mechanism that provides the position and orientation, i.e., six degrees of freedom, of a moving sensor relative to a fixed source. Attaching the sensor 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. One sensor was fixed to the hand segment, making available the exact location and orientation of the hand at each instant throughout the interval of motion. A second sensor was placed on the upper arm segment. Although the latter sensor did not enter into the feedback determinations, it enabled the acquisition of the kinematic history of the entire arm complex for further examination of changes in fixed synergy patterns and of the modification of the arm trajectories. The data acquisition rate was 60 Hz per sensor.

The touchplate, target structure, and ISOTRAC were interfaced to a PC-compatible microcomputer for real-time control and data acquisition.

2.2. Software

Software consists of the integration of routines for illuminating the target lights and acquiring the temporal and kinematic data, the presentation of feedback, and a user interface.

The control and acquisition software operates as follows. One of the three target lights is illuminated. The time at which the arm leaves the touchplate and the time at which the hand touches the target are recorded. The six kinematic trajectories from each of the two ISOTRAC sensors are acquired throughout the time interval from the activation of the target light to the touch of the target.

The feedback software delivers regulated auditory feedback during the trial. The following method was applied independently for each of the three targets. First, a normal path region for the hand sensor, or equivalently the end effector, was established, from the reaches of the normal group. The line joining the initiation and termination points of the reach was divided into a fixed number of equi-length segments, and an ellipse was constructed for each segment based on the standard deviation and the co-variance of the normal group within that segment. This sequence of ellipses forms a volume which was defined as the normal path region. Then, for any subsequent reach, whenever the hand sensor is within this volume the reach is considered to be in the normal path region. Next, the auditory feedback was designed. At each point in the ongoing reach, the position of the hand sensor in space is calculated in real time, and the segment of the normal path region to which it belongs is determined. If the hand sensor is within the ellipse associated with that segment, no tone is emitted. If the sensor is outside the ellipse, a tone is emitted immediately by the computer. The further outside of the ellipse the sensor is, over several multiples of the axes, the higher the frequency of the note; beyond that, a maximum frequency is employed. Thus, the subject receives information on the magnitude as well as the existence of the error.

The user interface is an interactive, screen-oriented program that retains the testing history of each subject and automates the details of the testing process. It displays the last session and trial completed by a given subject, exhibits the characteristics of the current trial which will be presented; and alerts the operator if the subject's arm is not on the touchplate. Upon termination of a trial, values associated with the reach parameters and with the feedback are given, and the next trial is activated. The user may override the automated features of the interface.
2.3. Subjects

A normal group consisting of 24 unimpaired subjects was tested. There were 9 males and 15 females, and all subjects were between the ages of 50 and 70 and right-handed. The normal group comprised of individuals with no history or physical findings of neuromotor or musculoskeletal disorder, and without recent administration of centrally acting pharmacological agents, recent illness requiring medical intervention or change in lifestyle, or undue painful conditions.

Two experimental groups, a practice group and a feedback group, were tested. Each group contained 8 subjects, 3 males and 5 females in the practice group and 4 males and 4 females in the feedback group. All subjects were between the ages of 50 and 70 and right-handed. Other selection criteria were: first occurrence of a unilateral left hemisphere lesion as verified by computerized tomography; visual acuity no greater than 20/40 with or without correction; evidence of ocular stability with functional saccadic and pursuit movements; absent visual spatial and visual field deficits, and visual acuity neglect; normal hearing; functional expressive and receptive language; cognitive function performance of everyday skills; and impaired but not absent tactile, pain, vibratory, and kinesthetic sensation. Exclusion criteria were: presence of other neurological or muscular conditions; presence of joint disorders affecting range of motion of joints of the right upper extremity, including recent trauma or pain; use of centrally acting pharmacological agents presumed to affect neuromotor function or recovery of function; fibrous illness within the last two weeks; severe cardiopulmonary decompensation; and micturition disturbance. Finally, the subjects had to be able to achieve a reaching distance of 75% to two of the three targets.

2.4. Protocol

The three targets were placed at shoulder height, and at 90% of the sum of the arm segment lengths from the shoulder to the IP joint, which is also referred to as the end effector. One target was in plane with the shoulder and the end effector, one target was 20 degrees to the left and one 20 degrees to the right measured from the shoulder. These are referred to as Targets A, B, and C, respectively. Because of the way in which the blocks for the targets were mounted to the stick, each target faced the subject. It is emphasized that each target was the same distance from the shoulder. The subject was seated and harnessed at the upper torso in the wooden chair facing the target structure. The armrest of the chair was adjusted so that when the elbow rested on it, the upper arm was perpendicular to the ground.

The hand was placed in a fist with the pads of the fingers resting on the palm. The thumb was placed comfortably inside the fist so as not to interfere with the fingers, making sure that it preceded the IP joint during the reach. This configuration was secured by wrapping the hand in a self-adhesive ace bandage. The wrist was placed at 10 degrees of extension, and the wrist and fist were immobile throughout the reach. This was accomplished by means of a carpal tunnel syndrome brace. The metal piece was replaced by foam that could be molded to achieve a 10 degree bend; this also eliminated metal that would interfere with the magnetic field of the ISO-TRAK. The targets were touched with the end effector, i.e., the IP joint.

The initial position was with the upper arm perpendicular to the ground, the elbow at 90 degrees of flexion, and the forearm midway between pronation and supination. The final position was with the IP joint on the target or as close to the target as possible, and with no deliberate forearm pronation or supination.

A typical reach trial proceeded as follows. One of the target lights was illuminated, and the subject, located the target visually or by his own pace. A gentle computer tone was then emitted to signify that the subject could begin the reach whenever he or she was ready. The subject performed the reach, and for trials involving feedback, auditory feedback was given throughout the reach. The touch of the target extinguished the light and terminated the trial; in cases where the subject did not touch the target, the trial ended after 15 seconds had elapsed. Thus, the auditory feedback is a knowledge of performance, and the extinguishing of the light is a form of knowledge of results. It was emphasized to the subject that this is not a reaction time task, and that the movement should proceed at a comfortable speed. Subjects in both experimental groups, practice and feedback, were familiarized initially with the task by means of passive movement of the hand to the target by the therapist.

Each subject in the normal group was tested on three occasions, without feedback, to establish repeatability of arm movement. Each session consisted of 42 trials with 14 trials for each target, and all trials randomized. A different random sequence of trials was used for each session. Each session began with some illustrative trials for familiarization and to establish consistent reaches and a natural speed.

Each subject in the two experimental groups, practice and feedback, was trained on 18 occasions, three times per week over a period of 6 weeks. The feedback group consisted of 42 trials consisting of three trials per day, for 24 trials consisting of consecutive times, practice group and back group. A di for each session, trials in each session, adaptation rate, repeat groups, a final test after training; learning, to the three targets rat no feedback. Each for familiarization that the feedback same amount of practice, and that both the subjects of knowledge group received the training.
The armrest of the elbow rested on it, the ground, with the pad of the thumb was placed the fingers, making using the reach. This using the hand in a 1st was placed at 10 and 1st were immo- was accomplished not brace. The metal could be molded to eliminate metal to field of the ISO- and the end effectors,

upper arm perpendicular to degrees of flexion pronation and with the IP joint as possible, and a separation follows. One of the he subject, located see. A gentle com- the subject or the subject was ready, for trials involve- as given throughout, extinguished a case where the 1st trial ended after auditory feedback the extinguishing of results. It was not a reaction could proceed at a two experimental familiarized intensive movement of was tested on three with repeatability trials of 42 trials trials randomized, was used for each extensive trials for stent reaches and stent groups, pro- cessing, three times per week over a six week period. Each session consisted of 42 trials. The first nine trials and the last nine trials consisted of the three targets randomly presented three times each with no feedback. The middle 24 trials consisted of each target presented eight consecutive times, without auditory feedback for the practice group and with auditory feedback for the feedback group. A different sequence of trials was used for each session. The first and last nine non-feedback trials in each session were used to evaluate learning and adaptation, respectively. For the practice and feedback groups, a final non-feedback session was conducted two weeks after training was completed for a final evaluation of learning. This session consisted of 42 trials with the three targets randomly presented 14 times each with no feedback. Each session began with illustrative trials for familiarization and warm-up. It is important to note that the feedback group by default also received the same amount of practice as the group designated practice; and that both the practice and feedback groups received knowledge of results, whereas only the feedback group received knowledge of performance feedback.

Figure 1 illustrates a subject executing a reach trial on the testing system.

3. Results

The normal path region for the end effector, produced from the data acquired from the normal group, was evaluated. For each of the two experimental groups, practice and feedback, reach parameters were defined and analyzed to identify differences in the trajectory of the arm evidenced in the sessions, in adaptation and learning, and in the targets.

3.1. Normal path region

Figures 2, 3, and 4 illustrate preliminary normal path regions for the end effector as obtained from the normal group. Each plot is a cross-sectional view of the volume that defines the normal path region for one target, derived from all subjects for one of the sessions. Each plot consists of 336 points, one from each of the 14 trials to the target for each of the 24 subjects. The view is along a straight line from the initiation to the termination point of the end effector. The abscissa is horizontal movement and the ordinate is vertical movement.

The amount of variation in the end effector path region decreased monotonically from the first to the third session, with the variation in the second session closer to that of the third. Figures 2(a) and 2(b) show a midsection of the normal path region for Target A for Session 1 and Session 3, respectively, revealing a wider scatter of points in Session 1. The difference in variation is likely due to the necessity for a certain amount of familiarization in order for unimpaired subjects to attain a steady state of path performance. Because of this, the first session was excluded from the construction of the final normal path regions.

The spread of the end effector path region among subjects and trials is wider during the midsection of the path and narrower at each end, giving rise to fusiform shaped path regions. Figures 3(a), (b) and (c) show an initial section, midsection, and final section, respectively, of the normal path region for Target B for Session 3. The fusiform shape may be explained by the fact that there is a common well-defined initiation and termination point in the reach, with an infinite number of possibilities for the interior portion.

There is a distinct right lateral curvature in the end effector path region for Targets B and C, and a more linear region for Target A. This is sharply depicted in Figure 4, a midsection of the normal path region for Target C for Session 3. Recall that Target B is in plane with the shoulder and end effector, while Target A induces a contralateral reach and Target C an ipsilateral reach. A similar result was noted for the same reaching task in unimpaired three-year-old children [6]. A study of reaching for planar hanging targets in unimpaired adults also produced this curvature in the end effector path in a minimum energy optimal control model which was verified experimentally [12].

3.2. Reach parameters

Each of the two experimental groups, practice and feedback, was examined separately with a repeated
measures analysis of variance, to determine the effect of the treatment on reach performance. Reach parameters were defined and analyzed independently for differences between the first and last sessions, between the adaptation and learning trials within sessions, and among the three targets.

Twenty reach parameters having biomechanical or clinical importance were considered. These were divided into seven categories. The first category consists of three parameters that describe the orientation of the hand at the end of the reach. The second has four parameters measuring the displacement of the end effector from the target at the end of the reach, along with its three orthogonal components. The third category contains one parameter, a measure of the linearity of the path of the end effector. The fourth has three parameters pertaining to oscillations of the end effector. The fifth has two parameters concerning the timing of the reach. The sixth consists of four parameters that show the relationship of the path of the end effector to the normal path region. The seventh category consists of three parameters that describe the orientation of the upper arm and the path of the elbow. The categories and parameters are abbreviated and defined in Table 1.

Each of these parameters was analyzed under three effects. First, the 18 adaptation and learning trials from Session 1, i.e., the 3 adaptation reaches to each of the 3 targets and the 3 learning reaches to each of the 3 targets, were averaged for each subject and this set compared to the analogous set from Session 18. The intention was to show the effect of the practice or feedback after 18 sessions of training. Second, the 18 adaptation trials from Session 1 and Session 18, i.e., the 3 adaptation reaches to each of the 3 targets from each of the 2 sessions, were averaged for each subject and this set compared to the analogous set of learning reaches from Session 1 and Session 18. This was to demonstrate whether the effect of practice or feedback immediately after training changed after some time had elapsed. Third, the 12 adaptation and learning trials from Session 1 and Session 18 for Target A, i.e., the 3 adaptation and 3 learning reaches to Target A from each of the 2 sessions, were averaged for each subject and this set compared to the analogous sets for Target B and for Target C. This was to reveal the effect of differences in various motor synergies. These three effects will be referred to as by session, by time, and by target. It is underscored that all trials used in the analyses were without auditory feedback.

The effect by session was of greatest interest in this study. It was predicted that in the session effect, for the practice group the parameters in Categories II and V would show the greatest change. These have the properties that they are inherently associated with the goal of the practice group which was merely to touch the target, and that improvement in these parameters would assist in that goal. It was further predicted that in the session effect, for the feedback group the parameters in Categories IV and VI would be altered the most. These are clearly associated with the goal of the feedback group which was to improve path performance, and bettering the values of these parameters would enhance the quality of that performance. The results will be presented for the effect by session in the practice group first and then in the feedback group, next for the effect by time in the practice then the feedback group, and finally for the effect by target in the practice and feedback groups. Results are reported for $p < 0.05$. 

![Cross-sectional views of the midsection of the normal path region of Target A: (a) Session 1; (b) Session 3.](image)

Fig. 2. Cross-sectional views of the midsection of the normal path region of Target A: (a) Session 1; (b) Session 3.

![Cross-sectional views of the midsection of the normal path region of Target A: (a) Session 1; (b) Session 3.](image)

Fig. 3. Cross-sectional views of the midsection of the normal path region of Target A: (a) Session 1; (b) Session 3.
3.2.1. Practice group session effect.

Several parameter values showed a significant difference by session, i.e., after the 18 practice sessions, in the practice group. In Category II, Dd decreased ($F = 5.07; 1, 10; p = 0.048$); in Category V, Movement.Time decreased ($F = 0.95; 1, 10; p = 0.025$) while Av.Speed increased ($F = 7.96; 1, 10; p = 0.018$); and in Category VI, Time.Out decreased ($F = 8.23; 1, 10; p = 0.017$). These are primarily related to the goal of the practice group to touch the target, and all are in the direction of improvement. Dd provides the main measure of the accuracy of target acquisition. Movement.Time and Av.Speed taken together reflect the speed of the reach. Time.Out pertains to maintaining the normal path region. The decrease in Dd implies that the final position of the end effector became closer to the target, this measured as the point-to-point distance between the end effector and the target at the termination of the reach. However, the shortening of this distance was not attributable to the end effector getting consistently closer to the target in any of the three component directions, as evidenced by the lack of change in Dx, Dy, or Dz. The decrease in Movement.Time and increase in Av.Speed imply a faster movement to the target. The interpretation of Time.Out depends on how certain other parameters change. It is important to note that the decrease in Time.Out together with the decrease in Movement.Time suggests that the reason that less time was spent outside the normal path region is because the overall time of the reach was shorter and
not because less of the reach was actually spent outside
the normal path region. This is further supported by the
task of change in the percent of movement time spent
outside the normal path region, %Time.Out, which
implies that the same proportion of the reach was spent
outside the normal path region. A study of the same
reaching task with knowledge of results but without
knowledge of performance feedback, as in the present
case for the practice group, in three-year-old children
with cerebral palsy also showed a decrease in movement
time [6]. Other studies of a similar reaching task
without feedback in patients in the chronic stroke period
showed an increase in average and maximum velocity
and a decrease in movement time [16].

3.2.2. Feedback group session effect

Other parameter values showed a significant differ-
ence by session in the feedback group. In Category I,
Az decreased ($F = 8.00, 1, 10; p = 0.018$); in Cate-
gory II; Dx decreased ($F = 13.37, 1, 10; p' = 0.004$); in
Category IV, Av.Disp.Changes.Dir decreased ($F = 6.07, 1, 10; p = 0.033$); and in Category VI, Time.Out,
decreased, ($F = 19.74, 1, 10; p = 0.001$), ($F =
10.85, 1, 10; p = 0.008$), ($F = 13.09, 1, 10; p =
0.005$), and ($F = 12.03, 1, 10; p = 0.006$), respectively. These are primarily related to the normal path
region information given as knowledge of performance
to the feedback group and the emphasis of the feed-
back training on staying in the normal path region, and
all are in the direction of improvement. Az and Dx
pertain to the closeness of the hand to the target in the
medial/lateral direction at the end of the motion, and
provide a measure of the accuracy of target acquisition
in that one direction alone. Av.Disp.Changes.Dir reflects
the diameter of the actual path used. Time.Out,
together are direct measures of the goodness of the
reach with respect to the path. The decrease in Az and
Dx means that along the lateral coordinate the final po-
sition of the reach was actually spent outside
the normal path region. However, the effector and
maintained use determinant is possible if
Dx was not in the point the reach. It
does not bro decrease in Dy and normal path re-
strained may be due path region
of swarving the practice with the
reason path region of the over
less of the rea.
sition of the end effector became closer to the target. However, the point-to-point distance between the end effector and the target at the termination of the reach remained unchanged, seen as no change in Dd, the main determinant of the accuracy of target acquisition. This is possible since there were no changes in the Dy and Dz components of the final position and they may even have had non-significant increases, and the change in Dx was not sufficient to cause an overall improvement in the point-to-point measurement of the accuracy of the reach. The main observation is that the end effector was not brought further forward toward the target. The decrease in Dx without an accompanying decrease in Dy and consequently in Dd may occur because the normal path region forces the end effector into a laterally constrained area, but does not urge the end effector toward the target. The decrease in Av.Disp.Changes.Dir may be due to the fact that remaining in the normal path region is served by a reduction in the amplitude of swerving. It is important to note that, in contrast to the practice group, the decrease in Time.Out together with the lack of change in Movement.Time implies that the reason that less time was spent outside the normal path region cannot be attributed simply to a shortening of the overall time of the reach but that in actuality less of the reach was spent outside the normal path region. This is verified by the decrease in the percent of movement time spent outside the normal path region, %Time.Out, which shows that a smaller proportion of the reach was spent outside the normal path region. The decreases in Av.Disp.Out and Max.Disp.Out imply that the reach was spatially closer to the normal path region even when it was outside the region.

### 3.2.3. Practice group time effect

Only one parameter value showed a significant difference by time, i.e., between the adaptation and learning trials, in the practice group. In Category III, El.Ee.Lin decreased (F = 5.52 1, 10; p = 0.041). El.Ee.Lin is a measure of how close the actual path that the reach takes is to a straight line between the initial position of the end effector and the target. The decrease implies that reaches were more linear immediately after practice than at a later time.

### 3.2.4. Feedback group time effect

Likewise, few parameter values showed a significant difference by time in the feedback group. In Category VII, Upper.Arm.Final.El and Upper.Arm.Av.El both decreased, (F = 8.04 1, 10; p = 0.018) and (F = 5.11 1, 10; p = 0.047), respectively. These do not appear to be related to the feedback, but both are in the direction of improvement. Upper.Arm.Final.El and Upper.Arm.Av.El pertain to the elevation of the

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<th>Abbreviations and definitions of the categories and parameters</th>
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<tr>
<td>I. Final hand orientation</td>
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<tr>
<td>Az final azimuth angle of the hand</td>
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<td>El final elevation angle of the hand</td>
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<tr>
<td>Ro final roll angle of the hand</td>
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<tr>
<td>II. Final end effector displacement from the target</td>
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<tr>
<td>Dx final distance of the end effector from the target center</td>
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<tr>
<td>in the medial/lateral direction</td>
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<tr>
<td>Dy final distance of the end effector from the target center</td>
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<td>in the anterior/posterior direction</td>
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<tr>
<td>Dz final distance of the end effector from the target center</td>
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<tr>
<td>in the inferior/superior direction</td>
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<tr>
<td>Dd final distance of the end effector from the target center</td>
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<td>III. End effector path linearity</td>
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<tr>
<td>El.Lin ratio of the path to the displacement for the end effector</td>
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<td>IV. End effector oscillation</td>
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<tr>
<td>Num.Changes.Dir number of changes of direction of the end effector</td>
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<td>Av.Disp.Changes.Dir average displacement of the changes of direction of the end effector</td>
</tr>
<tr>
<td>Max.Disp.Changes.Dir maximum displacement between any two consecutive changes of direction of the end effector</td>
</tr>
<tr>
<td>V. Timing</td>
</tr>
<tr>
<td>Movement.Time movement time of the reach</td>
</tr>
<tr>
<td>Av.Speed average speed of the reach</td>
</tr>
<tr>
<td>VI. End effector and normal path region relationship</td>
</tr>
<tr>
<td>Time.In amount of time that the end effector is outside the normal path region</td>
</tr>
<tr>
<td>%Time.In percent of the movement time that the end effector is outside the normal path region</td>
</tr>
<tr>
<td>Av.Disp.In average of the distance of the end effector from the normal path region when it is outside</td>
</tr>
<tr>
<td>Max.Disp.In maximum of the distance of the end effector from the normal path region when it is outside</td>
</tr>
<tr>
<td>VII. Upper arm orientation and elbow path</td>
</tr>
<tr>
<td>Upper.Arm.Final.El final elevation angle of the upper arm</td>
</tr>
<tr>
<td>Upper.Arm.Av.El average of the elevation angles of the upper arm</td>
</tr>
<tr>
<td>Elb.Ee.Lin ratio of the path to the displacement for the elbow</td>
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upper arm, which determines the height of the elbow. The decreases in Upper.Arm.Final.El and Upper.Arm.Av.El imply that the upper arm was held at a smaller angle, or equivalently the elbow was held at a lower position, for trials immediately after feedback than for trials at a later time. This behavior was true at the end of the reach as well as throughout the reach. Reaching with an exaggerated elevation of the upper arm is common in this population. Possible biomechanical explanations are that it employs the scapula rather than the shoulder muscles to move the arm mass, there is less spasticity in the horizontal plane, the elbow does not have to work against gravity the horizontal plane, or it allows more scapula and clavicle movement which can bring the end effector closer to the target. A study of the same reaching task with the elbow braced not to exceed 150 degrees of extension in unimpaired adults also showed reaching with an exaggerated elevation of the upper arm [11]. It was postulated that there is a perception that the end effector can be brought closer to the target under this configuration of the arm.

3.2.5. Practice and feedback groups target effect

Many parameter values showed a significant difference by target, i.e., among the three targets, in both the practice and feedback groups. These predominantly appeared in Categories I, Final hand orientation; II, Final end effector displacement from the target; IV, End effector oscillations; and V, Timing. These differences are not surprising since the targets themselves demand different kinematic responses and also require different synergy patterns. Final hand orientation would be expected to differ for targets in different locations in the workspace of the arm, irrespective of any impairment. Final end effector displacement from the target, End effector oscillations, and Timing, which differ among targets despite the fact that the targets are equidistant from the shoulder, may be influenced by the stage of synergic recovery.

Table 2 summarizes these results, indicating significance for each parameter for the effect by session, time, and target within the practice and feedback groups.

4. Discussion

The vast majority of patients deemed Target A, the contralaterally located target, to be the easiest. This is consistent with the stages of motor recovery and the fact that the recovery process can stop at any point. Target A can be attained by a volitional movement within the stereotyped whole limb extensor synergy which is an early stage of recovery, whereas Targets B and C require volitional movement in isolated joint out-of-synergy patterns which is a later stage of recovery.

The initial and terminal segments of the reach were the most difficult to execute, with the interior segment showing better control. The initiation of movement in general has a unique set of biomechanical requirements [10], and the termination of reaching requires the support of a large arm mass over the relatively long time interval during which endpoint accuracy is being refined. For the feedback group, these difficulties are compounded by the fact that the initial and terminal segments are also the narrowest portions of the fusiform normal path region.

Patients used the auditory feedback in a manner that evokes comparison with other studies directed toward modifying movement by means of auditory feedback training [13]. Specifically, at the beginning of training, the execution of the task assumes the form of a pointwise search to find the correct location as dictated by the feedback, often resulting in large fragmented oscillations and a poorer performance than that which would be achieved without the feedback. Later, the execution may become smoother and more successful as the task demands are internalized and the feedback is less attended.

Patients in the feedback group reported that when they improved their performance to a target, it was because they were able to visualize the path to that target from the feedback, and that they could not improve their performance, it was because they could not visualize the path. Some subjects described their strategy as deliberately reaching toward the space to the right of the target because this kept the hand in the normal path region and caused it to terminate accurately on the target. It may be commented that such subjects discovered the right lateral curvature of the normal path region.

Several recommendations for future studies can be made from the experiences of the present study. The lure of the target is too strong, causing some patients in the feedback group to become preoccupied with touching the target and less focused on remaining in the normal path region; more motivation for concentrating on the path should be supplied. The initial position of the forearm midway between pronation and supination was too difficult for some patients, and other options should be allowed. The composition of the reach was not affected by practice alone, and it may not be necessary to examine this group further. The majority of
The study demonstrated that modification of the trajectory can be accomplished during the practice period and that the "mirror" mainscan is strongest immediately after feedback. This suggests that the strategy used in this study, as well as its practice alone, may improve performance. The feedback required for auditory feedback is the same in both conditions. The results are consistent with the idea that feedback can be modified, and that the strategy used in this study is strongest immediately after feedback. This suggests that the strategy used in this study, as well as its practice alone, may improve performance. The feedback required for auditory feedback is the same in both conditions. The results are consistent with the idea that feedback can be modified.
to serve more patients. It may also be possible to configure the system as a home-based system for patient or family directed therapy, thereby expanding formal therapy sessions.

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References


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The purpose (FOS) of imputed drome (DS) is 2 years old; 16 children with and without FOS abilities. Amb Residents' print angles were 0.08 in standing

Keywords: Cognitive, plantar...
Azimuth – angle of lateral deviation
roll – revolving axis


Purpose: To examine effectiveness of an intervention for chronic upper extremity hemiparesis by means of trajectory modification via auditory feedback. Also, attempted to evaluate learning and adaptation via within trial comparisons.

Background: Characteristics of the reaching movements of hemiparetics have been widely studied in motor control. Characteristics of the reach of individuals with hemiparesis are decreased elbow extension with increased trunk flexion (Cirstea & Levin); multiple acceleration and deceleration profiles; and increased time to peak velocity (Trombly). Clinicians often observe lack of scapula/humeral disassociation, decreased upward rotation of the scapula, increased shoulder elevation, humeral internal rotation, trunk flexion, and decreased ability to couple shoulder and elbow movements. Clinicians often use tactile and verbal feedback to address these issues. These authors examined the use of auditory feedback during task performance (reaching) to improve the smoothness of the trajectory of individuals with upper extremity hemiparesis. A group of normal individuals were used to determine normal trajectories to the endpoints. The feedback group was compared to a group which practiced reaching w/o feedback but focused on endpoint accuracy.

Methods: Training for the practice and feedback group occurred 3x per week for six weeks. Each session had 42 trials which included: nine initial trials (3x3) w/o feedback; followed by 24 trials w/feedback for the experimental feedback group and then followed by the last nine trials w/o feedback. Two weeks after training, a non-feedback session was conducted for both groups to determine learning.

1) NORMAL PATH REGION: variation of end effector path decreased from first to third session. The spread of hand path regions is wider in the middle of the trajectory than at the initiation and endpoint. Ipsilateral reaches and those in the sagittal plane have a lateral curvature of the hand pathway. This was not seen in the contralateral reach.

2) HEMIPARETIC GROUPS: Twenty reach parameters (divided into seven categories) were determined for comparison between feedback and practice group. The categories include: (I) final hand orientation; (II) final effector displacement from target; (III) end effector path linearity (IV) end effector oscillations; (V) timing (movement time and speed); (VI) relationship between the end effector and the normal pathway; (VII) Upper arm orientation and elbow movement. These parameters were analyzed for three effects: (I) difference between first and last
session of each parameter (session); (2) difference within sessions of the adaptation and learning trials (time); and (3) differences among targets (target).

a. Session – Change from Session 1 to 18

Practice Group - Significance in category II – decrease in final effector displacement from the target. Change in category V. Decrease in MT and increase in speed. Change in category VI (effector vs. pathway) due to decrease in MT.

Feedback Group – Significance in categories I and II which are measures of target accuracy in one direction. Significant differences in category IV oscillations of the effector – decrease in the amplitude of the oscillations. And significant decreases in all parameters of category VI (how much the effector is outside the normal pathway) with no decrease in MT.

Time – Within sessions

Practice Group - Significance in category III – decrease in ratio of linear path to actual path AP/LP. Path more linear at end of practice.

Feedback Group – Significance in category VII which are measures of upper arm orientation and elbow path. Decreases in compensatory shoulder movement (shoulder elevation).

Target

Practice Group – Significance differences in in categories I, II, IV and V. Differences due to different kinematics of the 3 types of reaches.

Feedback Group – Same as above.

Discussion

Significance of category VII was noted in the time effect but not in the changes from session 1 to session 18. Authors stated that trajectory modification is strongest immediately after feedback training and diminishes over time. If this is true in a larger group of subjects, it would not be an ideal intervention. More subjects are needed to determine if this training could be retained. Also, a behavioral measure may demonstrate the relevance of the improvement in real life tasks. Combining intervention and learning into one study is problematic.