Sensory Stimulation Promotes Normalization of Postural Control After Stroke

Måns Magnusson, MD, PhD; Katarina Johansson, RN; Barbro B. Johansson, MD, PhD

Background and Purpose In a randomized study of hemiparetic stroke patients with a median age of 75 years, functional recovery was significantly better in those who received additional sensory stimulation (n=38), including electrostimulation, than in control patients (n=40) given the same physiotherapy and occupational therapy; group differences for balance, mobility, and activities of daily living were significant. The present study was designed to investigate postural control in patients who survived more than 2 years after stroke onset.

Methods The 48 survivors (mean, 2.7 years; range, 2.0 to 3.8 years), 22 from the treatment group and 26 from the control group, were compared with 23 age-matched healthy subjects. Subjects were perturbed by vibrators applied to calf muscles or with galvanic vestibular stimulation. We evaluated postural control in terms of sway variances or sway velocities and the dynamics of postural control as a feedback system using system identification with a model previously validated for human postural control.

Results Significantly more patients of the treatment group than of the control group maintained stance during perturbations (P<.01). Among patients capable of maintaining stance during perturbation, the control patients were characterized by significant divergence from normal values in two of the three characteristic parameters of dynamic postural control (ie, swiftness and stiffness; P<.05) compared with the treatment subgroup or age-matched subjects.

Conclusions The course of sensory stimulation enhanced recovery of postural function, an enhancement still significant 2 years after the lesion and treatment. The differences and near normalization of characteristic parameters of dynamic postural control among treated patients suggest that improved recovery after sensory stimulation may be achieved by patients regaining normal or near normal dynamics of human postural control. (Stroke. 1994;25:1176-1180.)

Key Words • acupuncture • cerebrovascular disorders • hemiplegia • rehabilitation • stroke outcome

Hemispheric stroke often causes impairment in upright stance and gait. Adequate postural control is a prerequisite for stabilizing the body in upright positions during voluntary movements and for mobility. These abilities are essential for activities of daily living (ADL). We recently reported that sensory stimulation may improve functional outcome after stroke. Stroke patients given sensory stimulation recovered faster and to a greater extent than did control patients; group differences in mobility, balance, and ADL 3 months after stroke onset were significant. The difference in ADL remained significant 12 months after stroke onset (for details, see Reference 3). In the earlier evaluation of the patients, balance was assessed using a scoring system. However, it is preferable to ascertain the effect of therapy on postural control after hemispheric stroke with objective measurements. Several methods are available for this purpose. Because human postural control can be considered to be in part a dynamic feedback system, the evaluation of dynamic control may contribute knowledge beyond that obtained with other standard posturography procedures.

The aim of the present study was to ascertain, 2 years or more after the event, whether patients given sensory stimulation with acupuncture in addition to physiotherapy and ADL training would differ in postural control from untreated patients undergoing standard rehabilitation therapy only. We also aimed to compare the dynamic control of posture among patients who had recovered sufficient ability to maintain upright stance in the two groups with that in age-matched healthy subjects. An issue of special interest was to ascertain whether the treatment group would manifest any appreciable signs of approaching normalized responses.

Subjects and Methods Patients with severe hemiparesis of the left or the right side (median age, 76 years) were randomized within 10 days of stroke onset to a control group receiving daily physiotherapy and occupational therapy (n=40) or to a group that in addition was given sensory stimulation (n=38). Sensory stimulation was achieved with acupuncture using a total of 10 needles, placed according to traditional Chinese acupuncture points (Table 1) on both the paretic and nonparetic sides and kept in place for 30 minutes. In addition to manual stimulation, electric stimulation of 2 to 5 Hz was given to four needles on the paretic side. The magnitude of the stimulation was set to be sufficient to induce muscle contraction. The treatment commenced 4 to 10 days (mean, 6.5 days) after the onset of symptoms and was continued twice weekly for 10 weeks. After that time we had no further contact with the patients except that the patients were asked to complete a quality-of-life questionnaire at 6 and 12 months and a follow-up 1 year after stroke onset to evaluate ADL.

At the time of the present study, 48 of the initial 78 patients were still alive (22 in the treatment group and 26 control patients). At the time of stroke onset 5 of 17 in the treatment group and 2 of 9 in the control group had signs of slightly reduced sensation of touch on the affected side. In the treatment group 2 of 17 in the treatment group and 1 of 9 in the control group had diabetes, but none of those subjects had any manifest polyneuropathy. One control patient did not
TABLE 1. Approximate Sites of Traditional Chinese Acupuncture Points

| 1. | Two hand widths below patella and 4 cm lateral to the tibia |
| 2. | One hand width below patella and 4 cm lateral to the tibia |
| 3. | At the anterior lowermost corner of the head of the fibula |
| 4. | On the middle of the belly of the musculus adductor pollicis longus when it is contracted |
| 5. | Lateral on the volar side of the elbow |
| 6. | On the dorsal side of the arm between the ulna and the radius about 5 cm proximal to the wrist |
| 7. | On the vertex of the head, at the crossing of a line drawn between each external auditory canal and the midline |
| 8. | One hand width above the patella and in the midline of the thigh |
| 9. | Dorsal aspect of the hand into one of the interossal muscles |
| 10. | On the dorsal aspect of the foot, in the skin between the first and second toe |

want to participate in the present study and was excluded. One patient from the treatment group was excluded because of a possible inner ear disorder. The 21 remaining patients in the treatment group had a mean age of 74.2 years; mean age of the 25 control patients was 74.8 years (Table 2). Of the subjects from whom data could be gathered in all postural recordings, 7 patients had a hemispheric lesion on the left side and 10 on the right side in the treatment group, and 4 had a lesion on the left side and 3 on the right side in the control group. The initial findings of the surviving patients included in the present study compared with all patients who first entered the trial are given in Table 3. The patients were compared with 23 age-matched normal subjects (13 men and 10 women; mean age, 76.0 years [range, 54 to 89 years]).

At testing subjects stood erect but relaxed on a force platform, with heels together and feet at a 30° angle, arms crossed over the chest, and eyes either closed or focused on a mark on the wall at a distance of 1.5 m. The subjects were exposed to perturbations in the form of either a vibratory stimulus applied to the calf muscles, which caused anteroposterior movement, or galvanic stimulation of the vestibular nerves, which caused lateral movement. Body movements in the anteroposterior and lateral planes were recorded with the force platform and sampled by a COMPAQ 386/20 computer equipped with an Analog Devices RTI 815 AD card. Sampling was done at 33 Hz during vibratory perturbations of different amplitudes and at 10 Hz during perturbation according to pseudorandom binary signal (PRBS) schedules. Analytical software (386-MATLAB, Mathworks Inc) was used for analysis of the data.

TABLE 2. Status and Ability to Stand Among Survivors of Stroke for ≥2 Years

<table>
<thead>
<tr>
<th>Treatment Group (n=21)</th>
<th>Control Group (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y (mean±SD)</td>
<td>74.2±9.9</td>
</tr>
<tr>
<td>Can perform tests</td>
<td>17</td>
</tr>
<tr>
<td>Cannot complete tests</td>
<td>2</td>
</tr>
<tr>
<td>Cannot stand unaided</td>
<td>2</td>
</tr>
</tbody>
</table>

*Two subjects whose recordings were lost because of computer failure are included.

TABLE 3. Activities of Daily Living and Balance Score of Patients Included in Present Study Compared With All Patients Initially Studied

<table>
<thead>
<tr>
<th>Time After Stroke Onset</th>
<th>Treatment Group</th>
<th>Control Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All* Present</td>
<td>All* Present</td>
</tr>
<tr>
<td>Balance score</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(max, 21)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;10 df†</td>
<td>8.6±4.2</td>
<td>10.2±3.2</td>
</tr>
<tr>
<td>1 mo</td>
<td>14.6±4.0</td>
<td>15.8±2.9</td>
</tr>
<tr>
<td>3 mo</td>
<td>16.1±3.9</td>
<td>17.7±2.6</td>
</tr>
<tr>
<td>12 mo</td>
<td>12.9±4.3</td>
<td>16.3±2.1</td>
</tr>
</tbody>
</table>

Max indicates maximum score. Values are mean±SD.

*From Reference 3.
†Randomized before study.

Three different tests were done, each with the patients’ eyes both open and closed. Two different tests were done with a vibratory stimulus applied to the calf muscles. In one test the subject was perturbed by five periods of vibration of 0.4-mm peak-to-peak amplitude at 20, 40, 60, 80, or 100 Hz in a pseudorandomized order; the sway velocities were calculated for each of these periods and for resting stance without perturbation. In addition, the subject was exposed to vibration at a constant frequency of 60 Hz given according to a PRBS schedule with pulses of between 0.5 and 8 seconds for 205 seconds, preceded by a 30-second recording of unperturbed resting stance. Data were evaluated as the sway variance in the anteroposterior plane and were used for system identification of a third-order ARMAX model of an inverted pendulum previously validated as a model for control of upright human stance. The normalized parameters of the transfer function, ie, swiftness, stiffness, and damping, were then compared between groups (Figure). The normalized parameters were compared with the parameters of proportional, integrative, and derivative (PID) control, which are well known from the fields of system identification and automatic control.

Bipolar, binaural galvanic stimuli at a peak-to-peak amplitude of 1 mA delivered by a custom-built constant-current generator were used to induce mainly lateral sway. Two 4×3-cm coal-rubber electrodes (CEFAR) were applied, one to each mastoid, and the stimuli were given according to a computer-controlled PRBS schedule identical to that used for the vibratory stimuli. The galvanic stimulation was given so that either the right or the left ear was stimulated. Body sway was evaluated as the variance of the lateral body moment as recorded by the forces actuated by the feet on the force platform.

Statistical analysis was performed on a Macintosh computer using JMP software (SAS Inc). Fisher’s exact test was used to compare the data for the subgroup that could perform all six tests and for the subgroup that could not, in both the treatment and control groups. One-way ANOVA was used to compare the treatment group, control group, and healthy subjects in terms of sway velocities under open- and closed-eyes conditions. Student’s t test was used to analyze differences between groups at each stimulus frequency, after the data had been checked for normal distribution with the Kolmogorov-Smirnov test, and group differences in moment variance in the anteroposterior plane during vibratory stim-
Top, Schematic representation of the effects of the characteristic parameters of human postural control symbolized as the corresponding effects of proportional, integrative, and derivative control. Stiffness corresponds to proportional (spring action), damping to derivative (dashpot action), and swiftness to integrative (integral over time) control. Middle, Bar graph shows characteristic normalized parameters of dynamic postural control when standing with open eyes. Bottom, Bar graph shows characteristic normalized parameters of dynamic postural control when standing with closed eyes. Note that swiftness and stiffness values for the treatment group tend to approach those for age-matched normal subjects. Values are mean and SD. *Significant difference of P<.05, control patients vs treatment group and normal age-matched healthy subjects.

Results

One of the 26 surviving control patients declined to participate, and 1 of the 22 survivors of the treatment group was excluded because of a possible additional inner ear lesion that resulted in asymmetrical hearing. These 2 patients are not included in Table 2, which shows the ability to stand among the survivors 2.7 years after stroke onset. Significantly more of the treatment group (17 of 21) than of the control patients (9 of 25) could perform all six tests (P<.0025, Fisher's exact test). Those for whom data could be gathered from all tests for evaluation of postural control finally comprised 17 patients of the treatment group (13 men, 4 women; mean age, 74.9 years [range, 55 to 89 years]) and 7 of the control group (5 men, 2 women; mean age, 71.4 years [range, 55 to 85 years]).

Among those patients who could perform all six tests, there was no difference between the treatment group, control group, and age-matched healthy subjects in sway velocity, vibration-induced anteroposterior sway, or galvanic-induced lateral sway.

The differences in swiftness values imply that the control patients needed more time to reassume the initial equilibrium position after a perturbation than did the treatment group or the healthy age-matched subjects, under open- and closed-eyes conditions (Figure). The differences in swiftness values imply that the control patients reacted less markedly to a perturbation that caused deviation from the resting equilibrium position. Moreover, approximately the same stiffness values were obtained for the control patients under open- and closed-eyes conditions (Table 4), a finding in contrast to those obtained in the treatment group, in healthy subjects, and in previous measurements.

Discussion

Among those who survived 2 years or more after hemispheric stroke, the treatment group (ie, those who underwent a course of sensory stimulation with acupuncture in addition to a standard individual rehabilitation program) manifested better postural control, in terms of the proportion of patients capable of maintaining upright stance during perturbation, than did the control group of patients who underwent rehabilitation therapy only. Furthermore, patients who had had additional sensory stimulation obtained values approaching the normal for age-matched healthy subjects when the dynamics of human postural control were assessed with a previously validated system identification model.

Adequate postural control is needed to maintain upright stance and mobility and also serves to stabilize the human body in performing voluntary arm and head movements necessary in ADL. Adequate postural control is therefore of paramount importance in rehabilitation of the stroke patient. The quantification of postural control and the effect of rehabilitation treatment poses special problems in stroke patients, partly because of spontaneous recovery and partly because patients were not able to participate in recordings that required the ability to stand unaided before engaging in rehabilitation treatments.

The maintenance of upright stance with closed eyes while counteracting perturbations in the lateral or anteroposterior planes requires more than rudimentary
postural competence. There was a highly significant difference between the treatment and control groups in the ability to perform all six tests (ie, subjects with a good recovery of postural function, spontaneous or not) to focus the study on differences in the pattern of recovery rather than on whether or not there was recovery. This approach explains the lack of differences in sway velocity or sway variance between groups in the present study. If the subjects who lost their balance in one or more of the tests had also been included, significant differences would have been present. However, overall differences in postural control between the groups are already evident from comparison of the numbers of subjects who could remain standing and endure perturbations (Table 2).

Postural control is assumed to be based on visual, vestibular, and proprioceptive information. In the present study we used a vibratory stimulus applied to the calf muscles, which caused erroneous proprioceptive information, or pulsed galvanic stimulation delivered by a constant current generator, which caused erroneous vestibular clues. As the subjects stood with eyes either open or closed (to allow or exclude visual information), the experimental setup included perturbations associated with the sensory input of interest.

The postural control system of the standing human is by definition in part a dynamic feedback control. In the anteroposterior plane it can be described by a third-order model. A third-order system may be interpreted as an inverted pendulum but with extended control, including an integrative parameter. This third parameter is beyond what is necessary for a simple pendulum model. This approach does not require or suggest that the human body behaves only like a rigid one-segment unit but implies that the extended control function of the given model is sufficient to describe the dynamics of postural control in quiet stance, as previously validated. Because the ability to maintain posture or to stabilize the upright human body during voluntary movements is of utmost importance to ADL, and because the present study revealed differences in the ways that those in the treatment and control groups who had recovered good postural stability achieved this ability, the present findings suggest that studying the dynamics of postural control can be of value in elucidating the effects of rehabilitation and different treatments.

Because the sensory stimulation was started 4 to 10 days after the onset of symptoms, reduction of a penumbra zone seems less probable as an explanation for these findings. The effect of expectation among patients given acupuncture has to be considered because special attention given to patients in rehabilitation therapy may accelerate their improvement, although such mechanisms usually fail to produce lasting effects in follow-up studies. We have therefore postulated that the sensory stimulation obtained with the present method might enhance the functional plasticity of the brain. A considerable functional reorganization within the brain after stroke has been demonstrated with positron emission tomography, including metabolic activation of both frontal lobes and cortex contralateral to the lesion. Muscle stimulation, including acupuncture, has been shown to induce the release of transmitters and neuropeptides, and it is possible that it also could stimulate trophic factors that enhance recovery. Although findings in the present study provide no clue as to a specific site of action, the near normalization of postural control that was still evident more than 2 years after the stroke suggests a lasting effect on the brain.

Our data also suggest that the enhanced postural competence in the treatment group is an effect of regaining near normal dynamic control of posture. The idea of enhanced plasticity of brain functions derives further support from differences in dynamic postural control between the two groups of patients who had regained adequate postural competence. Had rheological or unspecified effects been chiefly responsible for the observed improvements, one would not expect the significant divergence from normal in the dynamic properties of postural control that was manifest among the control patients but not the treatment group.

Another possible mechanism that might have contributed to the results of sensory stimulation merits consideration. It is well known from experiments on decerebrated animals, in which spinal programs for gait have been either electrically or pharmacologically invoked, that the step cycle is amenable to modification by such mechanisms usually fail to produce lasting effects in follow-up studies. We have therefore postulated that the sensory stimulation obtained with the present method might enhance the functional plasticity of the brain. A considerable functional reorganization within the brain after stroke has been demonstrated with positron emission tomography, including metabolic activation of both frontal lobes and cortex contralateral to the lesion. Muscle stimulation, including acupuncture, has been shown to induce the release of transmitters and neuropeptides, and it is possible that it also could stimulate trophic factors that enhance recovery. Although findings in the present study provide no clue as to a specific site of action, the near normalization of postural control that was still evident more than 2 years after the stroke suggests a lasting effect on the brain.

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### TABLE 4. Characteristic Parameters of Human Postural Dynamics When Perturbed by Vibration to Calf Muscles Among Subjects Who Endured All Tests (Subjects Standing With Open or Closed Eyes)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Treatment Group (n=17) (mean age, 74.9 y)</th>
<th>Control Group (n=7) (mean age, 71.4 y)</th>
<th>Healthy Subjects (n=23) (mean age, 76.0 y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open eyes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swiftness</td>
<td>2.76±0.92</td>
<td>3.68±0.67*</td>
<td>3.08±2.82</td>
</tr>
<tr>
<td>Stiffness</td>
<td>5.27±2.11</td>
<td>3.38±1.56*</td>
<td>6.25±6.49</td>
</tr>
<tr>
<td>Damping</td>
<td>2.12±1.22</td>
<td>1.41±0.55</td>
<td>2.52±1.59</td>
</tr>
<tr>
<td>Closed eyes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swiftness</td>
<td>2.59±0.78</td>
<td>3.97±0.92*</td>
<td>3.26±1.67</td>
</tr>
<tr>
<td>Stiffness</td>
<td>6.34±5.20</td>
<td>3.16±1.15*</td>
<td>7.67±8.75</td>
</tr>
<tr>
<td>Damping</td>
<td>2.04±1.25</td>
<td>1.98±0.51</td>
<td>2.46±1.83</td>
</tr>
</tbody>
</table>

Values are mean±SD. *P<.05.
for review and Reference 20). Moreover, as recently demonstrated by Kato, cats whose lumbar spinal cord was unilaterally transected and longitudinally divided in the midline below the transection regain coordinated gait, including movements of the decoupled posterior limb. It is also known that acupuncture as well as other types of sensory stimulation can activate multiple neuronal pathways, leading to enhanced neuronal activity.21

It has been suggested that at the time of the motor command the neuronal control issues an “afferent copy” of the command (see Reference 21 for review). In the multisensory control of movements the afferent sensory information caused by the executed movement is compared with the efferent copy, resulting in an error signal. The error signal and the motor commands then amalgamate, forming the subsequent motor commands.2 It is conceivable that the application of sensory stimulation might furnish spinal neurons with input that promotes remodeling or restoration of the coordinated motor function of the affected limbs. Moreover, enhanced central nervous system plasticity, at either spinal or cerebral levels or both, can be expected to improve the effects of physiotherapy and ADL training.

The initial rationale for evaluating acupuncture as sensory stimulation was the increasing demand from stroke patients for alternative treatments. The results of the previous study5 warranted this study, and the present findings merit further investigations into the effects of sensory stimulation in the rehabilitation of stroke patients. However, it should be emphasized that acupuncture in combination with electrostimulation is one means of producing sensory stimulation, and other possible methods of creating similar stimuli might be as beneficial and should be investigated. Clearly, further studies are needed before recommendations are made to include acupuncture or other methods of sensory stimulation, such as transcutaneous nerve stimulation, in the treatment of stroke patients.

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References

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