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Impairment of Learning the Voluntary Control of Posture in Patients with Cortical Lesions of Different Locations: the Cortical Mechanisms of Pose Regulation

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The process of learning to produce voluntary changes in the position of the center of pressures using biological feedback was studied by stabilography in patients with hemipareses due to cerebrovascular lesions in the zone supplied by the middle cerebral artery. There were significant impairments to learning in all groups of patients, who had lesions in different sites, demonstrating that cortical mechanisms are involved in learning to control posture voluntarily. These studies showed that patients with lesions in the right hemisphere had rather greater deficits in performing the task than those with lesions in the left hemisphere. There were significant differences in the initial deficit in performing the task on the first day of training depending on the side of the lesion. All groups of patients differed from healthy subjects in that significant learning occurred only at the initial stages of training (the first five days). Learning at the initial stage in patients with concomitant lesions of the parietal-temporal area and with combined lesions with motor, premotor, and parietal-temporal involvement was significantly worse and the level of task performance at the end of the initial stage was significantly worse than in patient with local lesions of the motor cortex. The level of learning was independent of the severity of the motor deficit (paresis, spasticity), but was associated with the severity of impairment of the proprioceptive sense and the severity of disruption to the upright posture (asymmetry in the distribution of support pressures, amplitude of variation in the position of the center of pressures). The learning process had positive effects on the severity of motor impairment and on the asymmetry of the distribution of support pressures in the standing posture. Reorganization of posture during bodily movements occurred mainly because of impairment to the developed "non-use" stereotype of the paralyzed lower limb.

The question of the cortical regulation of posture cannot yet be regarded as answered. According to classical concepts [23], which continue to be accepted [12, 17], the motor cortex and the pyramidal system, along with the rubrospinal system (the lateral system of Kuypers), control the musculature of the distal parts of the limbs, especially the wrists/ankles and digits, while the axial musculature of the body and, thus, the maintenance of posture, is controlled by subcortical structures, such as the basal ganglia [6, 9], the cerebellum [6], and the reticulo- and vestibulo-spinal systems (the ventromedial system of Kuypers) [11, 23]. At the same time, there is extensive evidence for the role of the motor cortex in controlling postural reactions responsible for shifting the center of gravity and maintaining balance [14, 18, 20, 24]. However, this question has mainly been addressed in experiments on animals and there have been almost no systematic studies on the cortical control of posture in humans.

Lesions to pyramidal structures, manifest as hemiparesis in humans, are known not to disturb balance-maintaining spatial coordination to the same extent as, for example, lesions to various extrapyramidal structures. Nonetheless, disturbances in vertical posture seen in pyramidal lesions undoubtedly occur [1, 15]. Some authors have associated derangements in stability with

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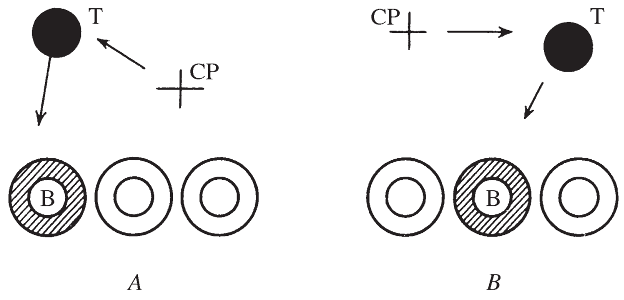

Fig. 1. Two fragments (*A* and *B*) of the BALLS computer game. CP is the projection of the center of pressures; T is the target, with which the player has to align the center of pressures, B is the basket into which the target then has to be moved. Arrows show the suggested trajectory for the center of pressures.

asymmetrical loading of the lesioned and intact legs and, as a result, shifting of the common center of gravity (CCG) towards the healthy limb in the frontal plane [15]. Others believe that impairment of balance functions is due to deficits in somatosensory information [22] and excessively slow correction of posture in response to changes in body position [13]. Thus, the question of the nature of postural disturbances in cortical-pyramidal lesions and lesions involving other cortical areas in humans remains unsolved. In particular, the extent of derangements in the voluntary control of the position of the CCG in patients with cortical lesions of different locations remains unclear.

On the other hand, experimental studies in animals show that the motor cortex has specific functions in the formation of new coordinative motor learning and in the reorganization of existing coordination [3]. The question of the extent to which the motor cortex and other cortical areas are involved in the process of learning a new posture in humans can be studied during the process of specialized rehabilitation training.

Biocontrol methods based on stabilograms (STG) with visual feedback [8] are increasingly used in the training of patients to maintain balance in neurological clinics: a monitor screen is used to show the coordinates of the center of pressures (CP; the center of pressures is the isoline of the supporting pressures which, in static conditions, coincides with the projection of the center of gravity; in dynamic conditions (changes of posture), however, the trajectory of the center of pressures is different from that of the center of gravity) of a subject standing on a force platform. This method has been shown to have positive influences on postural stability, postural asymmetry, walking speed, and the ability to perform the activities of daily living [8, 21, 25]. However, we have found only a small number of reports describing studies of the learning process itself. Hamman et al. [21] showed that the success rate in performing dynamic exercises with biological feedback (BF) provided by STG was independent of the degree of variation of the CP of the body in static tests. Wong et al. [25] demonstrated that the results of training patients with right- and left-sided foci were not significantly different.

Thus, the aim of the present work was to study the characteristics of the process of learning voluntary control of CP in conditions of biocontrol guided by the stabilogram in patients with post-stroke hemipareses, first with regard to lesions on different sides (right or left hemisphere), and secondly with regard to different sites of lesions (relatively local lesions of the motor cortex and the internal capsule or disseminated lesions in the posterior frontal or parietal areas).

METHODS

This study involved a total of 82 patients with hemipareses of different severities, due to cerebrovascular lesions in the territory of the middle cerebral artery, of different etiologies. The patients were aged 53.9 ± 11.0 years ($M \pm SD$); the mean duration of disease was 10.4 ± 8.8 months. Clinical signs of hemiparesis and the severities of clinical signs, spasticity, and sensory loss were assessed using the five-point scale developed by the Science Research Institute of Neurology (L. G. Stolyarova, A. S. Kadykov, G. R. Tkacheva, 1982). The degree of paralysis in our patients averaged 2.2. ± 1.3 points; spasticity amounted to 0.88 ± 0.76 points; musculoskeletal impairment was 0.79 ± 1.02 points (the maximum extents of paralysis, spasticity, and sensory disturbance were 5 points).

Assessment of impaired stability before and after training courses was based on stabilometric measures. The amplitude and the rate of oscillation of the center of pressures (CP) were measured in two 20-sec tests: one in a comfortable standing position and one in the central position; patients had to change the CP voluntarily to make it coincide with the geometrical center of the screen, and they then had to maintain posture throughout the study period. In the resting state, the loading on the lesioned limb in relation to the healthy limb was also determined.

All patients received the traditional complex of rehabilitation treatment. In addition, 43 patients, making up the experimental group, were trained by the biocontrol method using a stabilogram. The control group consisted of 39 untrained patients. These groups were comparable in terms of the main clinical factors.

In the first part of the study, patients in the experimental group were divided into two subgroups depending

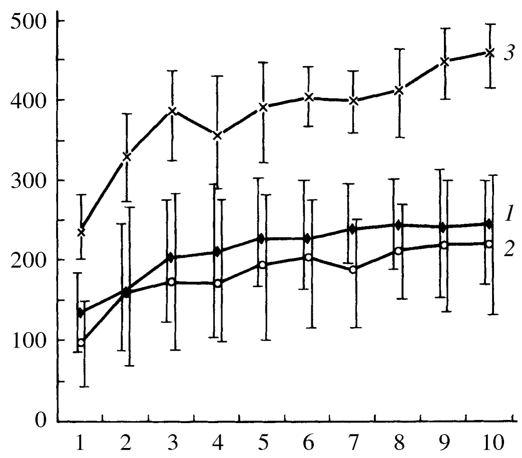

Fig. 2. Learning dynamics in patients with lesions on different sides. The abscissa shows training days and the ordinate shows the number of points awarded in the most successful game attempts each day; mean values for each group in points ($M \pm SD$). *1*) Patients with left-hemisphere foci; *2*) patients with right-hemisphere lesions; *3*) healthy subjects.

on the side of the lesion. The first subgroup consisted of 22 patients with foci located in the right hemisphere; the second subgroup consisted of 21 patients with left-sided lesions. Results obtained from trained patients were compared with those from a group of 15 healthy individuals, of mean age 48 ± 2.6 years. In the second part of the study, patients of the experimental group were divided into four subgroups according to the location of the lesion as shown by CT scans. The first subgroup (the "motor" subgroup) consisted of 12 patients with foci located in the cortical-subcortical areas of the main motor systems, involving the internal capsule, basal ganglia, and lower third of the central gyrus. The second ("premotor") subgroup consisted of 10 patients in whom additional foci were located in the posterior frontal gyrus. The third subgroup (the "parietal" subgroup) consisted of 11 patients, with foci located in the parietal-temporal region as well as the main motor zones. Finally, the fourth subgroup (the "combined" subgroup) consisted of 11 patients with widespread foci located in the motor, parietal, and premotor areas.

Training was performed using a Rist-131-AT computerized stabilogram developed at the OKB RITM in Taganrog [7]. This consisted of a force monoplatform, a monitor, and a computer running a suitable program supporting real-time studies. The patient stood on the platform in a comfortable position (feet apart to the width of the shoulders). The BALLS training game was used, in which the patient had to shift the CP (marked by a cursor on the computer screen) to coincide with a target, i.e., to move the cursor onto the target and move it into a designated basket (Fig. 1, *A*). Correct performance of the task resulted in the patient being awarded 10 points. If the target entered another basket, this was taken as an error. After performance of the task, for which the patient had up to two minutes (one game series), the position of the target and the designated basket were altered, in random order (Fig. 1, *B*). In general, patients were able to perform 5–40 tasks per series. Before the first game, patients were instructed as to how to perform the movement task. Movement had to be performed by shifting body weight from the right leg to the left and from the heels to the toes in different combinations. Daily training consisted of three series. Training courses consisted of 10 sessions. The results of the most successful series each day were assessed for each patient in terms of the number of points obtained and the number of errors made. Mean values were determined for each group and these were compared with each other and with measures for the healthy group. Correlation analysis of the relationship between learning and clinical and biomechanical factors was based on the most successful game series over 10 days. Statistical analysis was performed using the Statistica 4.5 program. Dispersion and regression analyses were used, along with correlation analysis by the Spearman method, and comparison of means by Student's test.

RESULTS

Characteristics of Learning Voluntary Posture Control in Patients with Lesions on Different Sides. The dynamics of training over 10 days in patients with lesions of the left and right hemispheres and in healthy subjects are shown in Fig. 2. The results obtained in healthy subjects were significantly greater than in patients with hemiparesis ($p < 0.001$). It was interesting that the most successful of three game series was in all groups the second series (in 56% of patients), which may be associated with adaptation to the task and formation (in the first days of training) or selection (later days) of motor strategies during the first series and tiring and loss of interest in the task during the third series. It should be noted that although the absolute results (Table 1) in patients with lesions of the left hemisphere were higher than those in patients with right-sided lesions, differences were significant only in terms of values obtained on the first training day ($p < 0.05$). Learning curves for patients of both groups were almost parallel, though the dynamics of learning in the "left-hemisphere" patients was characterized by greater stability and was not subject to sharp oscillations, as in "right-hemisphere" patients. The greater stability of motor habit formation in patients with lesions to the left hemisphere was also supported by the dynamics of errors committed (Table 1 and Fig. 3). The numbers of errors made by these patients were virtually

TABLE 1. Results of Training in Subgroups of Patients with Lesions in the Right and Left Hemispheres ($M \pm SD$)

Side of lesion	Points		Errors	
	Day 1	Day 10	Day 1	Day 10
Right hemisphere	97 ± 57	218 ± 92***	6.2 ± 2.0	3.5 ± 1.8***
Left hemisphere	135 ± 61	243 ± 67***	4.7 ± 1.8	4.1 ± 3.5

Notes. *$p < 0.5$; **$p < 0.01$; ***$p < 0.001$ (for Tables 1–4).

TABLE 2. Dynamics of Learning (in points) in Patients with Lesion in Different Locations ($M \pm SD$)

Subgroup of patients	Training day			
	1	3	5	10
"Motor"	169 + 67	254 + 80**	–	314 + 62**
"Premotor"	114 + 47	210 + 45**	–	255 + 51*
"Parietal"	105 + 64	163 + 77**	–	180 + 68
"Combined"	70 + 27	–	155 + 44***	133 + 47

constant. At the same time, "right-hemisphere" patients showed larger numbers of errors at the initial stage of training, with significant decreases in the number of errors as they assimilated the motor habit ($p < 0.05$). Attention is drawn to the fact that after training, patients with hemiparesis reached essentially the initial level seen in untrained healthy subjects (Fig. 3).

Learning Characteristics in Patients with Lesions in Different Locations. Learning curves in patients with lesions in different locations are shown in Fig. 4. This shows that the differences between groups affected both the initial deficit in performing the postural task (level of performance on the first day) and the learning process itself. The learning process could be divided into two stages in patients of all four groups. During the first 2–5 training days (first stage), there was marked improvement; learning was faster in the "motor" and "premotor" patient subgroups and was worse in patients with lesions of the parietal-temporal and "combined" lesions of the premotor and parietal areas. It is possible that a new motor strategy was formed at this stage. The second stage of learning then started, during which there was reorganization of coordination of the motor habit – disinhibition of movements interfering the coordination and fine control.

Learning was much slower at the second stage of the process. Learning dynamics differed in different subgroups. In "motor" and "premotor" patients, improvements were gradual and showed stepwise assimilation of sequential levels of complexity of the habit, occurring on average every three days. "Parietal" and "combined" patients remained at the previous level and further assimilation of movements did not occur.

Analysis of the absolute values on the first, third, and tenth days in patients of the first three groups and the first, fifth, and tenth days in patients of the fourth group showed that the best results were demonstrated by the "motor" patients (Table 2). Patients of the other groups showed, along with the usual motor problems, other problems – associated with derangements to the temporal and spatial organization of movement.

"Premotor" patients performed the task less successfully than "motor" patients. Their movements took longer periods of time, mainly because of decreases in the initial parts. Often, having performed an individual movement, they froze in indecision, glancing from the computer monitor to the instructor, waiting for further advice regarding actions. Sometimes, having performed the first part of the movement, these patients were unable to complete it without additional commands.

The poorest results were produced by the "parietal" and "combined" groups. Movement disorders were often accompanied in these patients by sensory or sensorimotor aphasia. The presence of these conditions significantly hindered explanation of the task and its understanding by the patients. These patients also showed clearly marked visual-spatial disorientation. They were poorly orientated in the direction of movement and sometimes, by shifting the CP to the left, unsuccessfully tried to "capture" the target by moving themselves to the right, confused the target and the basket, etc. Movements in these patients were characterized by "fussiness." Sometimes, having made many mistakes, these patients lost interest in performing the task.

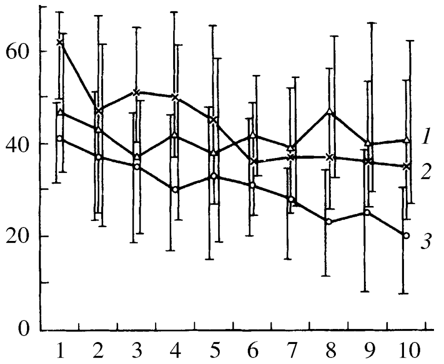

Fig. 3. Learning dynamics in terms of the number of errors committed in patients with lesions on different sides. The abscissa shows training days and the ordinate shows the number of errors committed in the most successful game attempts each day; mean values for each group in points ($M \pm SD$). *1*) Patients with left-hemisphere foci; *2*) patients with right-hemisphere lesions; *3*) healthy subjects.

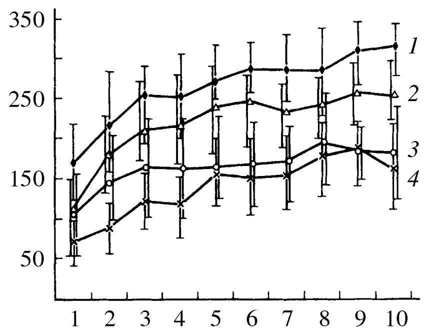

Fig. 4. Learning dynamics in patients with focal lesions in different locations. The abscissa shows training days and the ordinate shows the number of points awarded in the most successful game attempts each day; mean values for each group in points ($M \pm SD$). *1*) Patients with lesions of the motor cortex and pyramidal system ("motor" patients); *2*) patients with additional lesions to the premotor area ("premotor" patients); *3*) patients with additional lesions to the parietal-temporal area ("parietal" patients); *4*) patients with lesions of the parietal and premotor areas ("combined" patients).

Nonetheless, it should be noted that despite differences in the dynamics of training and its results, the very first part of the formation of the motor habit (maximum result on the first day) was identical in "parietal" and "premotor" patients.

Analysis of the results of training patients of different groups should, however, take cognizance of the fact that the curves shown in Fig. 4 characterize both the learning curves and the initial deficit in task performance, which was different in different groups (data for day 1, Fig. 4). These factors were separated by performing regression analysis, whereby each of the curves in Fig. 4 was extrapolated to produce the corresponding regression curve and was then compared with the intersect of the corresponding curves, to characterize the differences between the initial deficits and their slopes, to characterize the actual course of learning. The initial deficit in task performance was found to be significantly greater in patients in the "parietal" ($p < 0.05$) and "combined" ($p < 0.001$) patients than in the "motor" patients, and was also greater in the "combined" patients than in the "parietal" patients ($p < 0.01$, *t* test). At the same time, the slopes of the learning curves, which were significant in each individual group (showing that significant learning occurred in all groups), were insignificantly different between groups with the exception of the differences between the "motor" and "combined" groups and the "parietal " and "combined" groups ($p < 0.05$). Thus, the actual courses of learning were similar in most groups. However, interesting results were obtained when the first (first five days) and second (next five days) halves of training were considered separately.

In healthy subjects, both halves of the learning curve had slopes which were not significantly different from each other ($p > 0.05$). At the same time, differences between the slopes of the first and second halves of the curves (course of learning in the initial and final periods of training) in all groups were significant ($p < 0.05$ in the "motor" group, $p < 0.01$ in the "premotor" group, and $p < 0.001$ in the "parietal" and "combined" groups). Only the first halves of the learning curves of all groups had significant slopes, i.e., unlike the situation in healthy subjects, all groups of patients showed significant learning only in the first half of the training period. Comparison of the different groups showed that learning in this initial stage in the "parietal" and "combined" patients occurred significantly worse ($p < 0.05$) and the level of performance achieved in the first stage was significantly lower ($p < 0.01$ for the "parietal" group and $p < 0.05$ for the "combined" group) than in the "motor" patients.

Relationship between the Success of Learning and Various Clinical and Biomechanical Factors. (The term "success" here refers to the end result which, as shown above, depends on the initial level of task performance as well as on learning.) It was of interest to conduct a specific analysis of which clinical measures and biomechanical characteristics of the impairment in vertical posture significantly affected learning of voluntary control of posture, and the extents to which they did so. The results of this analysis are shown in Table 3. The nature of the biomechanical impairments of vertical posture in patients with hemiparesis will be analyzed in more detail in a separate report.

TABLE 3. Correlation Coefficients (*r*) for Measures of the Success of Learning and Some Clinical and Biomechanical Factors

Parameter	*r*
Severity of lower limb paralysis	–0.21
Spasticity	0.10
Deep sensation in the lower limbs	–0.29*
Mean rate of CP in the comfortable position	–0.21
Mean radius of CP in the comfortable position	–0.40**
Loading on the impaired leg	0.30*
Mean rate of CP in the central position	–0.41**
Mean radius of CP in the central position	–0.45***

TABLE 4. Clinical and Stabilometric Measures before and after Training in the Experimental and Control Groups of Patients ($M \pm SD$)

Parameter	Experimental group		Control group	
	before training	after 10 days of training	initial level	at 10 days
Severity of lower limb paresis (points)	2 ± 1.01	1.39 ± 0.68***	2.3 ± 0.8	1.8 ± 0.5*
Spasticity (points)	0.76 ± 0.80	0.7 ± 0.76	1.1 ± 1.3	1.0 ± 0.8
Deep sensation in the lower limbs (points)	0.85 ± 1.39	0.56 ± 1.05***	0.73 ± 1.8	0.65 ± 1.2
Mean rate of CP in the comfortable position (m/sec)	20.59 ± 7.80	18.2 ± 6.0	22.3 ± 7.3	22.0 ± 5.8
Mean radius of CP in the comfortable position (mm)	11.13 ± 5.93	10.71 ± 3.38	10.8 ± 0.3	10.7 ± 6.5
Loading on the impaired leg (%)	30.04 ± 11.74	38.9 ± 10.6***	29.08 ± 10.3	33.0 ± 7.6*
Mean rate of CP in the central position (m/sec)	26.50 ± 11.20	22.9 ± 8.2*	29.03 ± 8.3	27.0 ± 6.3
Mean radius of CP in the central position (mm)	11.06 ± 5.62	10.53 ± 5.11	10.6 ± 6.3	11.3 ± 5.6

Factors such as the severity of hemiparesis and the level of spasticity were found not to have significant effects on the formation of the new postural coordinations responsible for dynamic stability. Conversely, impairments of deep sensation, which accompany hemiparesis, correlated negatively with the success of training as measured in terms of the maximum point scores (Table 3).

As regards the rates and amplitudes of biomechanical measures characterizing the state of the vertical posture-maintaining functions, the results of training were found to depend significantly on the initial magnitude of oscillations (the mean radius of oscillation) in CP. The mean speed of the CP and the mean radius of oscillation of the CP in the central (model) position, as well as the mean radius of oscillation and magnitude of loading on the lesioned limb in the comfortable posture, were associated with the best learning outcomes. At the same time, the mean rate of oscillation of CP in the posture to which the patients were accustomed had no effect on learning the new posture (Table 3).

Thus, the degree of intrinsic motor dysfunction (the severity of hemiparesis and spasticity) had no effect on the nature of learning posture coordination. At the same time, the success of training depended on the accompanying sensory disturbances (decreases in deep sensation) and especially on the severity of lesions to stability (the amplitude and partial rate of oscillation of CP).

The Effects of Training on Clinical and Biomechanical Parameters. In its turn, training affected both the severity of motor impairment and biomechanical measures of posture stability. This is illustrated in Table 4, which shows several clinical and stabilometric measures from patients of the experimental group before and after training courses and from the control group who received traditional courses of rehabilitation therapy but no training by the biocontrol method using the stabilogram. The data presented in Table 4 show that patients of both groups showed improvement in the same parameters: there were decreases in the degree of paresis and increases in the loadings on the lesioned limb, though these changes were much more significant in the trained patients. It is important to note that these patients, unlike patients of the second group, had significant improvements in proprioceptive sensitivity and decreases in the rate of oscillation of the center of pressures when the platform was centered. At the same time, the amplitude (mean radius) of oscillations in CP did not change significantly.

DISCUSSION

Before assessing the cortical mechanism of learning the voluntary control of posture, we will consider the possibility of spontaneous recovery, which could affect the results obtained here.

Pure, or "spontaneous" recovery occurs at the earliest stages after strokes, during the first three months; according to some authors this can occur during the first six months, because of decreases in edema, absorption of damaged tissue, improvement in local circulation, and the development of collateral circulation [16, 19]. Temporarily inactivated but surviving neurons in the area of the focal lesion are released from inhibition [4], resulting in restoration of the damaged connections.

The mean time at which our patients were studied was 10.4 ± 8.8 months after their strokes. Thus, despite the large variation in the post-stroke period, most patients were studied well after the end of the period of spontaneous recovery.

At later times, recovery occurs because of mechanisms of compensatory rearrangement, based on the plastic properties of the nervous system. These result in the formation of new systems of temporary connections, which create a new organization for functions and perform these functions in the new conditions [2]. In other words, learning occurs.

Vertical posture is a movement habit learned in early ontogenesis and is based on the performance of the genetic program for standing. The questions of the extent to which its recovery in patients with damage in different sites is associated with the recovery of the original program and the extent to which recovery is associated with the reorganization and formation of new motor coordination, i.e., learning, is of significant theoretical interest both from the point of view of the structural organization of the original program for standing and from the point of view of studies of the roles of different structures in learning the new posture. The present study provides material for addressing both the first (characteristics of the impaired posture in patients with lesions of different sites) and the second (differences in learning the new posture in patients with different lesions) processes.

As mentioned above, special analysis of the biomechanics of postural impairments in patients with damage to different sites will be presented in a separate report. We note here only that different cortical lesions are accompanied by significant postural disturbances – a point which has been noted repeatedly by others [13, 15, 22] and which provides evidence for the existence of cortical mechanisms for performing the program underlying vertical posture.

The first point to note for analysis of the characteristics of learning the voluntary control of the center of pressures is that lesions of the motor cortex, be they isolated local lesions or lesions occurring in combination with lesions to other areas of the cortex, significantly deranged the process of learning the new posture: the learning curve and the maximum level of learning were significantly worse than in healthy subjects. This supports data obtained in animals demonstrating a role for the motor cortex in reorganizing postural coordination [3]. Finally, it should also be noted that apart from cortical lesions, our patients also had lesions to the basal ganglia, and we were thus dealing with combined lesions. However, the main differences between the various groups were in the severities and locations of cortical lesions, making it possible to assess the role of different cortical areas in learning to control posture.

Studies of the correlation between gait and the level of learning with the level of motor and sensory impairments showed that the nature and result of training depend mainly not on the severity of the paresis and spasticity as such, but on the accompanying disturbances to proprioceptive sensitivity and the severity of impairments to the initial posture (the magnitude of oscillation of CP). This indicates that the mechanism and pathways from the motor cortex for controlling limb movements and posture are different. Although lesions to the motor cortex and pyramidal system are accompanied not only by paresis, but also by postural abnormalities, postural derangements arise indirectly, because of the release of modulating pyramidal influences on brainstem structures; postural derangements are not directly associated with the severity of paresis. Data supporting the indirect effects of the motor cortex on the mechanisms of posture control have been obtained in animals [3].

We will now consider the relationship between the nature of learning the voluntary control of posture and the side of the lesion and the relationship between the gait and the extent of learning and the position of the lesion.

Comparison of the dynamics of learning in patients with right- and left-hemisphere foci showed no significant differences, probably because of the wide spread in values, which generally supports the view of Wong et al. [25], that that the differences between these groups of patients are insignificant. Nonetheless, throughout the study patients with foci in the left hemisphere demonstrated greater levels of success in learning, with more stable retention of the assimilated motor habit, which is in agreement with published data [10] on the better rehabilitation in patients of this type. This leads to the conclusion that the right hemisphere seems to have greater responsibility for organizing new postural coordination using a feedback signal than the left hemisphere. The many errors made by right-hemisphere patients on the first training day might be evidence for the delayed formation of the basic strategy, i.e., a rational program of action, in these patients. It is also possible that the right hemisphere has extensive involvement in providing for the retention of the coordination pattern of the postural movements in memory, which might be evidenced by the lesser stability of the movement habit during training in patients with focal lesions in the right hemisphere.

Analysis of the relationship between learning the voluntary control of the center of pressures and the position of the lesion needs to consider the two stages of motor learning – the stage of association, or formation of a general action strategy, its thought program (the “what to do” program) and the stage of forming the coordination pattern for the new movement, its coordination program (the “how to do it” program), in which the reorganization and inhibition of inadequate synergy and coordination take place [3]. In the present work we attempted to identify these stages, though this discrimination was very arbitrary in nature. Since the learning curves were quite clearly divided into an early, faster, and a subsequent, slower, stages, we suggested that the first period, when there were sharp increases in the results, was associated with the formation of a general strategy for controlling the center of pressures. It is, however, possible that this stage, when the patient understood how to shift the CP and solve the task, was limited to the first two days. In the latter case, the differences in the so-called initial deficit in task performance (data from the first day) also characterized the difference in the formation of the strategy for performing the task. The second stage started on day 3–5, when increases were smoother. This is most likely when further rearrangement in the coordination pattern of the already assimilated posture and movements and refinement of the formed habit occur.

It was significant that these stages of learning occurred differently in patients with damage in different locations. It was clear that both the motor cortex and the associative areas – the premotor and parietal – are involved in both the first and the second stages of learning.

The learning deficit in the initial stage was seen in all groups of patients, demonstrating the involvement of the motor cortex not only in reorganizing coordination but also in the process of forming the thought program. In the “parietal” and “combined” groups of patients, this deficit was significantly worse, which appears to demonstrate the important role of the parietal associative area at this first, cognitive stage of learning.

The second stage of learning – the stage at which coordination is rearranged and refined – was virtually absent in all groups of patients. This seems reasonable, as all groups of patients had lesions to the motor cortex, whose role in reorganizing postural coordination in learning had been demonstrated in several animal studies [3, 14, 20, 24]. It should, however, be borne in mind that this learning paradigm did not involve the patients acquiring a new, stable postural coordination but formed the habit of rapidly shifting the center of pressures towards the unexpected and unpredictable appearance of targets at different points of the screen with subsequent rapid shifting of the CP towards one of the baskets, i.e., the habit of rapidly controlling the center of pressures. In these conditions, even after selection of the optimal strategy for moving the CP at the first stage of learning, patients subsequently, in each test, had to solve the task of rapidly shifting the CP in previously unknown directions. It is clear that in this situation, problems associated with decision-taking and initiating displacements of the CP in “premotor” patients, as well as the problems of sensory integration and the sense of the body’s position in the extrapersonal space in “parietal” patients must play a significant role.

The relationship between the level of learning and the severity of the proprioceptive deficit seen here is evidence of the priority of sensory mechanisms in the task of learning the voluntary control of the center of pressures using biological feedback provided by the stabilogram. The degree of postural stability – the amplitude of oscillations of the center of pressures, which is itself significantly dependent on sensory mechanisms – also plays a very important role in learning. At the same time, the process of learning to control the position of the center of pressures has significant effects on motor systems, decreasing the severity of paresis and spasticity. One factor may be additional proprioceptive afferentation arising as a result of selective activation of various muscle groups during voluntary displacement of the center of pressures.

Thus, there is no doubt that cortical mechanisms are involved in the control of posture and learning the voluntary control of the center of pressures. A variety of cortical zones take part in these processes. The greatest disability in solving the task arises in patients with combined lesions of the motor and parietal areas or the motor, premotor, and parietal areas. A deficit in sensory integration and the perception of the body’s position in space in patients with parietal lesions is one of the major limiting factors and cannot be overcome during the training process.

CONCLUSIONS

1. Voluntary displacement of the center of pressures and learning to perform this task using biological feedback provided by a stabilogram were significantly impaired in patients with hemipareses due to cerebrovascular accidents in the territory of the middle cerebral artery.

2. Patients with lesions in the right hemisphere showed rather greater deficits in performing the task than patients with lesions in the left hemisphere.

3. Patients with lesions in different locations showed different deficits in task performance on the first day of training. The greatest impairment was seen in groups with accompanying lesions in the parietal-temporal area and combined lesions of the motor, posterior frontal (premotor), and parietal-temporal areas.

4. While healthy subjects showed significant learning over all 10 days of training, the learning process stopped in patients with hemipareses at the early stage, and no significant learning occurred during the second stage of training (days 5–10).

5. Learning during the initial stage was significantly worse and the level of performance achieved was significantly worse in patients with accompanying lesions of the parietal-temporal area and with combined lesions of the motor, posterior frontal (premotor), and parietal-temporal areas, as compared with patients with local lesions of the motor area.

6. The extent of learning was independent of the severity of the motor deficit (paresis, spasticity), but was associated with the severity of derangements in proprioceptive sensation and with the severity of derangements to vertical posture (asymmetry in the distribution of supporting pressures and the amplitude of oscillations in the center of pressures).

7. The learning process had positive effects on the severity of motor impairment and on the asymmetry of the distribution of supporting pressures in the standing posture. Postural rearrangements during body movements occurred mainly because of impairment in the formation of the "non-use" stereotype of the paralyzed leg.

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REFERENCES

1. N. A. Bernshtein, *The Physiology of Movements and Activity* [in Russian], Nauka, Moscow (1990).
2. A. M. Zimkina, "The neurophysiological bases of the compensation of external functions," in: *Clinical Neurophysiology* [in Russian], Leningrad (1972), p. 343.
3. M. E. Ioffe, *Mechanisms of Movement Learning* [in Russian], Nauka, Moscow (1991).
4. N. V. Konovalov, "Basic concepts in the question of functional recovery after stroke," *Zh. Nevropatol. Psikhiatr.*, **55**, No. 6, 401 (1955).
5. A. R Luriya, *Higher Cortical Functions in Humans* [in Russian], Moscow State University Press, Moscow (1969).
6. Zh. Massion, "Central coordination of pose and movement," in: *Associative Systems of the Brain* [in Russian], Nauka, Leningrad (1985), p. 18.
7. Yu. S. Sliva, I. V. Kondrat'ev, and O. V. Orlov, *Medical Information Systems* [in Russian], Taganrog (1993), Vol. 4, p. 120.
8. L. A. Chernikova, *Optimization of the Recovery Process in Patients following Stroke: Clinical and Neuropsychological Aspects of Functional Bioregulation* [in Russian], Author's abstract of thesis for doctorate in medical sciences, Science Research Institute of Neurology, Russian Academy of Medical Sciences, Moscow (1998).
9. K. B. Shapovalova, I. V. Yakunin, and M. I. Boiko, "Involvement of the head of the caudate nucleus in the mechanisms of conditioned reflex rearrangement of pose," *Zh. Vyssh. Nerv. Deyat.*, **34**, No. 4, 669 (1984).
10. V. N. Shmel'kov, *Restoration of Movement Potential in Patients with Post-Stoke Paralyses and Pareses and Focal Lesions in Different Cortical Hemispheres* [in Russian], Author's abstract of thesis for doctorate in medical sciences, Science Research Institute of Neurology, Russian Academy of Medical Sciences, Moscow (1979).
11. A. I. Shumilina, "The involvement of the pyramidal and extrapyramidal systems in motor activity in deafferented limbs," in: *Questions in Higher Nervous Activity* [in Russian], P. K. Anokhin (ed.), Academy of Medical Sciences of the USSR Press, Moscow (1949), p. 174.
12. J. Armand, O. Olivier, S. A. Edgley, and R. N. Lemon, "The structure and function of the developing corticospinal tract: some key issues," in: *Hand and Brain*, A. M. Wing, P. Haggard, and G. R. Flanagan (eds.), Academic Press, New York (1996), p. 125.
13. M. B. Badke and P. W. Duncan, "Patterns of rapid motor responses during postural adjustments when standing in healthy subjects and hemiplegic patients," *Phys. Ther.*, **63**, 13 (1983).
14. E. V. Birjukova, M. Dufosse, A. A. Frolov, et al., "Role of the sensorimotor cortex in postural adjustment accompanying a conditioned paw lift in the standing cat," *Exptl. Brain Res.*, **78**, 588 (1989).
15. R. W. Bohannon and P. A. Larkin, "Lower extremity weight bearing under various standing conditions in independently ambulatory patients with hemiparesis," *Phys. Ther.*, **65**, No. 9, 1323 (1985).
16. A. Brodal, "Self-observations and neuro-anatomical considerations after stroke," *Brain*, **93**, 664 (1973).
17. V. B. Brooks, *The Neural Basis of Motor Control*, Oxford University Press, New York (1986).
18. N. I. Burlachkova and M. E. Ioffe, "The analysis of the postural adjustment accompanying a local movement," *Aggressologie*, **20B**, 141 (1979).
19. W. W. Chambers, C. N. Liu, and G. P. McGough, "Anatomical and physiological correlates of plasticity in the central nervous system," *Brain Behav. Evol.*, **8**, 675 (1973).
20. M. E. Ioffe, N. G. Ivanova, A. A. Frolov, et al., "On the role of motor cortex in the learned rearrangement of postural coordinations," in: *Stance and Motion. Facts and Concepts*, V. S. Gurfinkel, et al. (eds.), Plenum Press, New York (1988), p. 213.
21. R. G. Hamman, I. Mekjavic, A. L. Mallinson, and N. S. Longridge, "Training effects during repeated therapy sessions of balance training using visual feedback," *Arch. Physiol. Med. Rehab.*, **73**, No. 8, 738 (1992).
22. F. B. Horak, "Clinical measurements of postural control in adults," *Phys. Ther.*, **67**, 1881 (1987).
23. D. G. Lawrence and H. G. J. M. Kuypers, "The functional organization of the motor system in the monkey," *Brain*, **91**, 1 (1968).
24. J. Massion, "Role of the motor cortex in the postural adjustment associated with movements," in: *Integration in the Nervous System*, H. Asanuma and V. J. Wilson (eds.), Igaku-Shoin, Tokyo (1979), p. 239.
25. A. M. Wong, M.. Y. Lee, J. K. Kuo, and F. T. Tang, "The development and clinical evaluation of a standing biofeedback trainer," *J. Rehab. Res. Dev.*, **34**, No. 7, 322 (1997).