STUDY ON IMPROVING HEEL STRIKE BY CONSTRAINT-INDUCED MOVEMENT IN PATIENTS WITH STROKE

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Abstract. *This is an ascertaining and ameliorative study that, through these two aspects, aims at checking to what extent constraint-induced movement therapy applied to the healthy lower limb can cause significant improvement in the affected limb in terms of increased active mobility of the ankle flexion, and integrating this mobility into the heel strike during gait. It is known that, when walking, these patients come into contact with the support surface with the forefoot or the entire sole instead of the heel. The research was applied to 16 patients with stroke pathology and a motor and cognitive status that gave them the opportunity to participate in the rehabilitation programme. This programme was intensive, lasting over a period of 3 weeks, 6 hours per day, and consisted of a set of exercises divided into a main programme made up of 12 exercises and a secondary one including 6 exercises – both performed under constraint-induced conditions. The latter, due to the different nature of the exercises compared to the former, had the role of determining the patient to transfer and integrate functional gains into a context closer to the activities of daily living, but without being mentally boring. Following the study, we believe that the benefits of this approach to lower limb rehabilitation should be considered and extended to post-traumatic pathologies that lead to negative repercussions on gait phases.*

Keywords: *heel strike, constraint-induced movement, stroke, active ankle flexion.*

Introduction

Stroke is one of the most debilitating conditions, causing approximately 9 million survivors of this disease worldwide to live with some degree of disability and handicap (Lamontagne & Fung, 2005). Of these, only about 50% will be able to carry out walking-based daily activities in their communities (Wolfe, 2000).

The features of gait functionality in stroke patients with hemiparesis raise some issues regarding the very ergonomics of the act of walking. This is because walking is characterised by low speed of movement and endurance, and, finally yet importantly, these patients show changes in the quality and flexibility of the gait stereotype. Regarding the average speed of movement, according to the literature, it varies between 0.5-0.8 m/sec (Nadeau et al., 2013), which represents approximately between 19%-60% of the movement speed of healthy elderly subjects (at the end of their 6th decade of life) (Murray et al., 1969). Muscle energy required by the poststroke sequelae is higher than for a person with normal gait. Intersegmental coordination between the upper and lower limbs while walking is severely affected (Olney & Richards, 1996). Overall, we can conclude that the gait of the hemiparetic adult after stroke is characterised by impaired intersegmental coordination, shorter step length with the lower limb on the affected side, longer duration of single-leg stance on the unaffected side and shorter on the affected side (Wong et al., 2004).

These problems are all the more serious as the possibility of moving in the outdoor environment becomes an important goal (Hösl et al., 2019). If, following a more or less satisfactory gait recovery, these patients can move relatively easily indoors, the same cannot be said about walking outdoors. This is because the outdoor environment usually raises climatic problems (walking against the wind, walking on rough terrain, walking on a ramp or slope, etc.), so it can disturb gait ergonomics by the lack of adequate compliance with certain qualitative parameters. Maintaining an efficient ability to walk is important because it is a substrate in the activities of daily living (Chen et al., 2005).

One of the important qualitative gait parameters around which all other parameters are built (dynamic balance, intersegmental coordination, speed of movement, etc.) is heel strike, which is performed at the beginning of the single-leg stance phase. It is known that patients with hemiparesis have a relatively high degree of spasticity in the posterior lower leg muscles of the affected limb (Cheng et al., 2010) simultaneously with hypotonia of the anterior and peroneal muscles. Consequently, the regulation between active flexion-extension of the ankle is detrimental to flexion. Because of this, the beginning of the single-leg stance phase - which normally corresponds to the heel strike - will be adopted by leaning either the forefoot or the entire sole on the support surface, thus creating the impression of a “collapsed foot” (Voigt & Sinkjaer, 2000). This dynamic attitude of the ankle joint corresponds to the clinical picture of adult motor neuron disease.

In this regard, some studies have been conducted, but they place an important emphasis on the heel-strike pressure (Meyring et al., 1997; Mizelle et al., 2006), without analysing its cause (control of the muscles that perform dorsiflexion under concentric-isometric-eccentric contraction conditions), which determines the heel-strike pressure on the walking surface. We mention this aspect because, in such an approach, conceptions that are not exactly correct in terms of recovering this parameter may arise. Following the analysed studies, it can be easily concluded that, during heel strike, these patients cannot concentrate their entire ground pressure force at the heel, but involuntarily distribute it to the midfoot or forefoot (therefore, dispersed pressure), arguing that, due to their weakened motor control, they are no longer as firm in terms of transferring the centre of gravity to the affected limb. We consider that, in the case of neurological stroke patients who have not lost their ability to walk independently (even if this is done with relative difficulty), the transfer of the centre of gravity to the affected limb is achieved to an almost equal extent as in healthy people; however, although this happens, the cause for which the pressure on the affected heel is not performed well enough is the inability to correctly execute ankle dorsiflexion, to sufficiently expose the heel to the ground.

Before addressing the purpose, objectives and methodology of the research undertaken, we highlight that all the above pathological gait characteristics in poststroke hemiparetic patients develop against the background of spatial hemineglect syndrome. It is expressed by the patient’s increased tendency not to take into account the spatiality on the side contralateral to the brain lesion (Kinsbourne, 1994), creating the impression that no stimulus acts favourably on this half of the body. Consequently, such patients, during walking and activities of daily living, will not have the initiative to move with the affected half of the body (Bailey & Riddoch, 1999), seeming that this part is continuously “dragged” after the healthy one.

Over time, specialists in the field of kinetic rehabilitation of patients with neurological status after stroke have approached in different ways gait rehabilitation parameters and gait as a whole. Various methods are proposed for this, such as treadmill training, in-water walking, use of robotic tools (Lokomat), mirror training to increase awareness of the affected limb. Some of these methods address walking either too analytically or too globally: those who address it analytically and obtain functional gains do not put increased emphasis on integrating these gains into broader contexts in which walking usually takes place (for example, the activities of daily living); those who address it globally relying on the development of quantitative parameters (step length, speed of movement) and dynamic balance lose sight of qualitative parameters (heel-strike angle), which can be a functional substrate in the development of ergonomic gait, translated into better autonomy of movement.

In contrast, constraint-induced movement therapy applied to the lower limb has the advantage that, against the background of restricting the freedom of movement of the affected limb, all functional gains obtained by initially performing simpler goal-oriented motor tasks are then transferred to a set of motor tasks with progressive complexity that require the patient to make an increasingly significant psycho-cognitive and motor effort. In addition, it has the double advantage that: 1) it leads to favourable results in a relatively short time – the approximate duration of therapy is between 2-3 weeks (Mark et al., 2013); 2) against the background of restricted joint mobility in the healthy limb, it forces the affected one to move in more and more complex ways – even if movements are initially performed in the pathological sphere with the help of synkinesis – and to experience as much as possible the whole set of proprioceptive and exteroceptive sensations. In this way, through systematic and intense repetition, neuroplasticity of the cerebral neural networks is stimulated, which will lead to remapping the area where the affected limb is represented, thereby reducing zonal cortical inhibition (Nudo et al., 2003).

The end result after therapy translates into a decrease in spatial hemineglect syndrome, which means bringing the affected lower limb back into consciousness, and once brought back there, kinetic work can be used effectively to regain gait parameters – in the case of our study, heel strike.

Research purpose

The study aims to determine the effectiveness of functional rehabilitation through constraint-induced movement therapy applied to the healthy lower limb of the patient with hemiparesis in order to improve heel strike as a qualitative gait parameter.

Research objective

It consists in highlighting the action mechanisms of constraint-induced movement therapy and their use for gait rehabilitation.

Research hypothesis

Constraint-induced movement of the healthy lower limb in the patient with hemiparesis and the use of the affected lower limb in performing therapeutic tasks lead to improved heel strike as a qualitative gait parameter, thus ensuring the rehabilitation of gait ergonomics, translated into closer-to-normal functional independence of movement.

Methodology

Participants

A group of 16 subjects participated in the research. Their diagnosis was poststroke hemiparesis lasting for less than 6 months.

The inclusion criteria were:

- hemiparesis after stroke;
- absence of pain in the lower limbs;
- ability to walk independently, even if this is done with relative difficulty;
- active flexion mobility in the coxofemoral joint of at least 40^o, and in the knee joint, of at least 20^o;
- satisfactory dynamic balance assessed by the Berg Balance Scale;
- normal cognitive state so as to understand verbal instructions;
- subjects who have expressed their consent to participate (informed consent);

The exclusion criteria were:

- age under 55 and over 72 years;
- movement-triggered mechanical pain in both the lumbar spine and the large weight-bearing joints;
- subjects who have not expressed their consent to participate;
- inability to maintain orthostatic balance independently;
- cardiorespiratory diseases that do not allow physical effort.

Instruments

The assessment of the 16 subjects was performed using the Gait Abnormality Rating Scale modified after van Swearingen (GARS-M) (Vandenberg et al., 2015) and was applied before starting the therapy to record the current level of subjects regarding heel strike as a gait parameter, and then, after completing the therapy, to highlight their progress. In our study, we used a 4-item scale to assess the heel-strike angle during step initiation. GARS-M involves the existence of items that aim to describe gait, which is associated with an increased risk of falling among people with neurological disorders (stroke, Parkinson’s disease, etc). Prior to GARS-M, the assessment of neurological patients was performed using unmodified GARS whose items described the same gait qualities. However, the modified scale items highlight the differences between neurologically affected people who have fallen and who have not fallen sometime in the past. Other items made it difficult to visually assess gait parameters or did not match the results of several evaluators.

In this study, certain parameters, such as the active flexion angle in the ankle joint, were measured using the Kinovea computer program applied to the video recording of each patient. Basically, we virtually applied markers to the lower limb segments on the video image and, depending on them, we made the measurements. Following these measurements, the assessment was performed through modified GARS.

We mention that, to obtain the most accurate quantification of the heel-strike item, the contact angles were assigned certain value ranges (expressed in figures) in order to know exactly the progress level of subjects. In this respect, we provide the following example: depending on the scale, the score progression did not take into account the degrees that the sole should have formed with the ground; during heel strike, quantification was done only in terms of obvious angle and poorly visible angle, each angle corresponding to a score. Thus, we considered that we could be more accurate in assessing the contact angle if we also used literature data quantifying in degrees the normal heel strike according to the biomechanical gait analysis and, depending on normality, we could give the other scores more accuracy.

Procedure

The research was conducted between March 2018 and February 2019. The participants benefited from physiotherapy sessions at the Rosana Medical Polyclinic in Bucharest. The treatment period for each subject was 3 weeks.

The kinetic programme consisted in performing certain motor tasks based on constraint-induced movement of the healthy lower limb, i.e. its joint mobility was restricted to the maximum with the help of a fixed knee orthosis – causing the impaired leg to move and, in this context, patients had to practise intensely 6 hours per day, for 3 weeks, the following exercises that composed the main and secondary programmes:

a) the main kinetic programme (composed of 12 exercises):

1) horizontal walking facing the direction of movement over a distance of 6 m, with self-imposed speed; in the first 2 days, the execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
2) horizontal walking with the back to the direction of movement over a distance of 6 m, with self-imposed speed, with alternating step; in the first 2 days, the execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
3) lateral walking with added step, horizontally, moving forward the healthy lower limb over a distance of 6 m, with self-imposed speed; in the first 2 days, the execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
4) horizontal walking over a distance of 6 m by going round the cones placed 1 m apart from each other; performance speed was self-imposed; in the first 2 days, the performance time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);

5) walking on an inclined plane over a distance of 6 m, with self-imposed speed; in the first 2 days, the performance time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
6) horizontal walking over a distance of 6 m, with an emphasis on the heel-strike phase, followed by the foot rolling on the ground, with self-imposed speed; in the first 2 days, the execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
7) horizontal walking over a distance of 6 m by stepping over obstacles positioned at a height of about 3 cm, with self-imposed speed; in the first 2 days, the execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
8) horizontal walking over a distance of 6 m, with the change of speed at a verbal command; in the first 2 days, the performance time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
9) horizontal walking over a distance of 6 m, with task performance: while walking, the patient "picks up" objects positioned on the walking surface; in the first 2 days, the task execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
10) horizontal walking over a distance of 6 m, with task performance: while walking, the patient catches with both hands a ball thrown by the physiotherapist (who is in front of the patient, at a distance of about 1.5 m), and then performs a chest throw with both hands; in the first 2 days, the task execution time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (2 lengths x 6 m);
11) climbing stairs (5 steps); climbing started with the impaired limb – because the orthosis did not allow initiating the step with the other limb – and, whenever needed, the patient was supported by the arm; in the first 2 days, the performance time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds, with a break of 1 minute (3 series);
12) descending stairs (5 steps); the descent started with the healthy lower limb (the one with the orthosis), because we were interested in getting the best possible control of support (especially controlled braking ability) on the impaired limb; for this exercise, the patient was supported by the arm whenever needed; in the first 2 days, the performance time was unlimited, then, starting with the 3rd day, it was necessary to perform the exercise in maximum 1 minute and 30 seconds (3 series).

b) the secondary kinetic programme (composed of 6 exercises):

1) walking forward with a gymnastic stick held by both ends above the head; every two steps with the impaired limb, the patient lowers the stick and concomitantly raises the knee so that the stick and the knee come into contact (6 lengths x 6 m);

2) walking forward with the alternating rotation of the head to the left, then to the right, at the verbal instruction of the physiotherapist; during this time, the patient must maintain the direction of movement (6 lengths x 6 m);
3) walking forward, the patient is tied with a waist strap attached to a rope that passes over a pulley and, after passing over the pulley, a weight is hung at its end; this pulley-weight system is placed in front of the patient, who must continue to move opposing the weight that pulls the patient forward – basically, the weight accelerates the gait, and the patient must control this acceleration (6 lengths x 6 m);
4) walking forward, the patient is tied with a waist strap attached to a pulley-weight system placed back to the patient; the patient must move forward to overcome that weight while moving (6 lengths x 6 m);
5) walking backwards, the patient is tied with a waist strap attached to a pulley-weight system placed in front of the patient; the patient must overcome that weight while walking backwards (6 lengths x 6 m);
6) walking forward in the direction of movement between two parallel lines marked on the ground (the distance between them is 50 cm); an elastic band is attached around the patient's waist; the therapist is placed laterally and pulls the band intermittently, then continuously from the side to disturb the patient's balance; the patient must walk without deviating from the space delimited by the two lines (6 lengths x 6 m).

In order to highlight the progress obtained, we performed, in the first phase, a statistical interpretation of the scores achieved by the group of patients for the heel-strike item, and in the second phase, a statistical interpretation of numerical values that were the basis to award scores for the same item.

The statistical program used for data processing was SPSS 15.

Results

Regarding the interpretation of the scores, in the initial assessment, the results of the group were as follows: average 1.65, median 1.5, score 1 frequency 8, score 2 frequency 6, and score 3 frequency 2. In the final assessment, the results were: average 0.37, median 0, score 0 frequency 10, score 1 frequency 4, and score 2 frequency 2. Following these statistics, it is found that the heel-strike phase in the initial assessment of subjects predominantly has a "poorly visible" walking surface contact angle (dorsiflexion between 0^o and 20^o); instead, in the final assessment, after applying constraint-induced movement therapy to the lower limb, this angle has improved reaching dorsiflexion values between 20^o and 30^o, which corresponds to an "obvious angle".

The progress rate between the two assessments was 76.92%. Table 1 shows these values, and Figure 1, the average scores for the two assessments.

Table 1. *Group results – GARS-M scores in the two assessments*

Assessment	Score frequency				Total score	Progress rate	Average	Median
	0	1	2	3				
Initial	0	8	6	2	26	76.92 %	1.65	1.5
Final	10	4	2	0	6		0.37	0

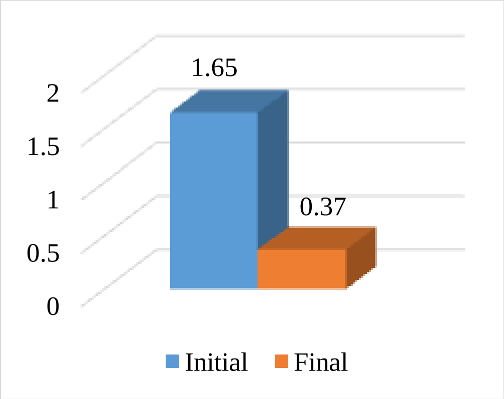

Figure 1. Graphical representation of average GARS-M scores

Due to this process and the appropriately individualised and iterated adaptation, constraint-induced movement therapy led to better recruitment of muscle groups, which resulted in better active mobilisation of the ankle joint dorsiflexion.

Regarding the statistical interpretation of numerical values that were the basis to award scores for the scale item, we find that the average value (in degrees) has increased from 5.56^o in the initial assessment to 17.12^o - in the final assessment. The result reveals an average improvement of 11.56^o in the contact angle. The median increased from 5^o to 21^o, and the standard deviation significantly increased from 7.33 to 7.38. Minimum and maximum values increased in the context in which all subjects improved their performance. The progress rate between the two assessments also increased by 207.9%. We mention that this item of the modified Gait Abnormality Rating Scale is highly important because the other qualitative and quantitative gait parameters depend on the greatest possible range of motion of the contact angle during the initiation of the previous step. Table 2 shows the statistical results obtained by subjects for the heel-strike item, and Figure 2 is the graphical representation of contact angle values in the two assessments.

Table 2. *Group results – Heel strike in the two assessments*

Assessment	Average	Average difference	Median	Standard deviation	Coefficient of variability	Minimum	Maximum
Initial	5.56	11.56	5	7.33	131.83%	-6	15
Final	17.12		21	7.38	43.10%	0	22
	Progress rate: 207.9 %						

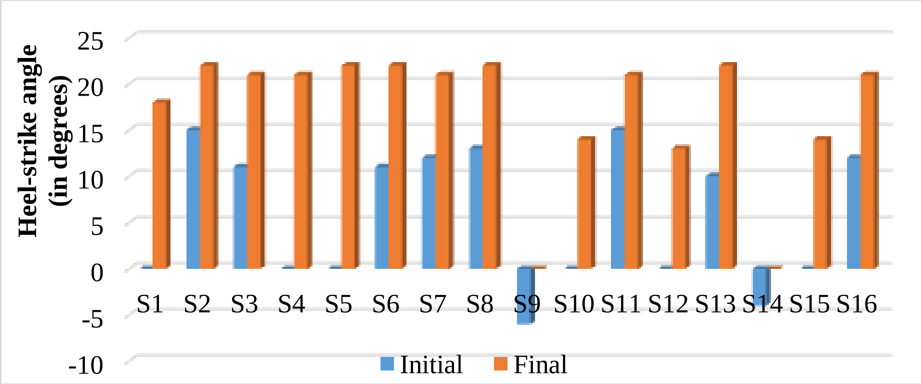

Figure 2. Graphical representation of the heel-strike angle

Subject 2 recorded the highest progress in both the initial and final assessments (15.22^{o} initially and 22^{o} finally). This progress was possible due to a very low musculotendinous spasticity-stiffness association, the subject having a mild form of stroke, which allowed him to improve his active flexion-extension mobility in the tibiotarsal joint.

Subject 9 recorded the lowest progress in both the initial and final assessments (-6^{o} initially and 0^{o} finally). In this case, no increased spasticity was noted in the posterior lower leg muscles, but only stiffness during the eccentric work as a result of insufficient recruitment of the anterior region muscles responsible for executing an approach angle with the normal heel. Constraint-induced movement therapy applied to the affected lower limb acted in this very direction (by restricting the degree of freedom of the unaffected one) to "activate" the ankle flexors simultaneously with the knee and hip flexors, the latter – as strong muscles – becoming "starters" for the former and providing considerable nerve irradiation.

The statistical interpretation of numerical values (heel-strike degrees) that formed the basis to award scores was performed using the nonparametric Wilcoxon test. Since the returned $p = 0.0002$, it appears that there is a probability of less than 1% to fail in making progress and a probability of 99.98% ($1-p = 0.9998$) to make progress. Given that $p < 0.05$, it follows that the null hypothesis is rejected. Table 3 shows the results of the nonparametric Wilcoxon test.

Table 3. *Results of the approach angle to the ground*

Test	Wilcoxon	
	Z	p
	-3.7312	0.0002

Discussion

Neuromotor rehabilitation is an internal process that takes place inside the central nervous system. This process occurs when a neurological patient tries to perform a certain motor task but fails to successfully complete it and therefore the task has to be permanently adjusted until it is correctly performed. Throughout the process, the patient is required to provide considerable psychophysical effort. Hence the important aspect of our study, namely that the patient is allowed to initially perform movements in the pathological sphere with the help of synkinetic, compensatory movements, and subsequently, based on these and in conjunction with constraint-induced movement, verbal guidance, systematic repetition and continuous variation of motor tasks, to choose increasingly goal-oriented exercises and reach a higher degree of accuracy in performing motor gestures. We mention that the action mechanisms of constraint-induced movement therapy of the lower limb are based on the direct stimulation of certain reflexes such as positive supportive reaction, movement reflex, crossed-extension reflex, which, if intensely repeated, automatically lead to reshaping the cerebral neural networks, thus decreasing inhibition in the affected cortical area. This reduced inhibition in the affected area will result in acquiring superior movement stereotypes in both qualitative and quantitative terms, which will be consciously stored in the central nervous system. Further, through the continuous variation of increasingly complex motor tasks, the previously stated movement stereotypes will shift from the conscious to the automatic sphere, constituting in turn a "substrate" for the internalisation of higher motor gestures in terms of complexity. Basically, constraint-induced movement therapy, through the mobility restrictions imposed on the healthy limb, "forces" the central nervous system to continuous neuroplasticity.

We consider that, throughout this process, constraint-induced movement therapy has led to better recruitment of muscle groups in the antero-lateral lower leg and thus to better active mobilisation of the ankle joint dorsiflexion during heel strike. For the most part, the literature addresses gait rehabilitation parameters and gait as a whole in the neurological patient starting with paying more attention (from the very beginning of the process) to analytical movements, then gradually trying to integrate them into increasingly complex sets of movements. This is certainly a fair point of view. However, we believe that we should not be so strict but allow the patient, in the first phase, to use compensatory, synkinetic movements, and then try to refine motor gestures by getting rid of these movements; this should not necessarily be done by directing the patient's attention to "how to get rid of synkinesis", but by always integrating new motor tasks to be performed, which, in themselves, force patients to work as correctly as possible. At a later stage, they should be associated with the patient's attention and self-control.

Conclusion

In the functional rehabilitation of the lower limb, the application of constraint-induced movement therapy, although it initially allowed the performance of gross movements (unlike classical approaches that rely, from the beginning of neuromotor rehabilitation, on performing precise movements) associated with synkinesis subsequently marked by systematic repetition, verbal guidance, uninterrupted motivation, increased attention and the continuous change of motor tasks, patients were able to perform movements with a much higher level of coordination in a short time – 3 weeks, considerably reducing synkinetic movements; this process was obviously based on the ability of the cerebral areas to reorganize functionally, a process that we "modelled" through an original programme.

Of great importance is the fact that the progress made in the 3 weeks persisted for up to 4 months, these results being in accordance with the data from the international scientific literature (Wolf et al., 2006).

Although the walking cadence did not represent an assessment criterion for the subjects, by its very involvement in the quality of gait, we should take into account that it was also favourably influenced after constraint-induced movement therapy. Even if the average normal number of steps per minute in a healthy person is about 70-80, the final average did not exceed the value of 48.31 (that is, about 50% of the average normal steps per minute) in the investigated group of subjects. However, considering that the group started from an initial average of 38.25 steps per minute, it gained another 10 steps per minute in just 3 weeks. These data allow us to anticipate that, against the background of constraint-induced movement therapy applied to the lower limb, classical physiotherapy is rationally supplemented with adapted sports activities (depending on the current psychophysical condition, comorbidities, age, gender, degree of interest in movement) and thus patients with hemiparesis after stroke can make major progress (even close to normality) in terms of obtaining satisfactory walking cadence.

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