THE USE OF OPTIMAL MULTICHANNEL STIMULATION IN THE CORRECTION OF HEMIPLEGIC GAIT

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Introduction

Hemiplegia is one of grave diseases of the contemporary world by which 2-3% of population is affected. The rehabilitation of hemiplegic patients is a complex problem, consisting of physical rehabilitation and the rehabilitation of speech, and demanding the solution of many psychological problems (1). In this exposition we shall be dealing with the rehabilitaion of locomotion apparatus only. Our aim is to transform the pathological pattern of gait into as normal a pattern as possible. As a means to it, functional electrical stimulation (FES) will be used (2,3).

The first orthóses working on the principle of FESE were peroneal surface braces (4,5), and implanted braces (6,7). The experience obtained by their use showed the need for a surface stimulator for the correction of gait in swing phase (8). Although the effects of stimulation were evaluated qualitatively only, the results showed that the three-channel stimulation eliminated a number of anomaliés which the one-channel peroneal brace could not have done. The results of positioning of ankle joint by means of antagonistic pair of muscles had a good influence on the development of research in the direction of multi-channel stimulation, with which, it was proved, it is possible to provoque artificially movements whose static and dynamic characteristics are none the worse from woluntary movements (9).

The purpose of our work was to determine in an experimental way optimal stimulation sequences which should best approach the hemiplegic gait pattern to the normal gait pattern. The parameters of gait were measured by goniometric measuring system by which goniograms and basograms of both legs were measured, and these were collected and processed by the ON-LINE processor computer (11,12). The gait was evaluated by quantitative evaluation methods (13). The result thus obtained was compared with the qualitative kinesiologic clinical analysis of gait and by the the qualitative analysis of goniograms. In this way the correctness of quantitative evaluation was compared. The six-channel (14) programmed surface stimulator was used for stimulation. Experiments were done on five male hemiplegic patients of different age, from 39 - 72 years of age. The correction of gait on three patients, acheived by optimal stimulation sequences and evaluated by qualitative kinesiologic clinical analysis, is described in the reference (15).

In the present study the results of experiments on two hemiplegic patients are given. The correlation of kinesiologic clinical analysis with mathematically and statistically based evaluation is done.

Methodology

Optimal stimulation sequence is determined iteratively. During single measuring turns the number of stimulated muscle groups and the time distribution of stimulation sequences is changed. We usually begin with gait without stimulation, then successively stimulation channels are added and at the end the gait is again measured without stimulation. The improvement in gait correction is controlled by ON LINE quantitative measurement of gait and by clinical analysis. Each sequence consists of 100 - 120 steps. The initial stimulation sequence and the choice of muscle groups to be stimulated are decided in accordance with qualitative kinesiologic analysis of gait and on the basis of our knowledge about the kinetics of gait (16, 17), and about muscle coordination (18). We rely also on EMG activity of main muscle groups of leg during normal gait pattern(19). By the stimulation of of each single muscle group we want to eliminate or diminish typical anomalies - of gait. The approach was good, for , with the elimination of anomalies - the characteristic parameters of gait were improved, particularly the symmetry and the repeatability. The distribution of stimulation sequences is such that it eliminates as much as possible anomalies ; therefore we stimulate in swing and in stance phase. In one cycle of gait, only one train of stimulation impulses with constant amplitude appears. The amplitude and the position of stimulation electrodes are determined so as to obtain a plastic movement. Three stimulation channels are triggered by the heel-on time, and the three others by the heel-off time. With respect to pathological gait pattern, muscle groups are stimulated in the following way :

- the Pretibial Group stimulation begins with the swing phase and ends at 20% of the gait cycle after the stance phase. This is true for the patient with an extension gait pattern. For the patient with a flexion gait pattern, stimulation is interrupted at the end of the swing phase.

- Muscle Triceps Surae stimulation begins with the heel-off time (i.e. the last third of the stance phase) if we want to strengthen the push-off phase, and it begins at the second third of the stance phase, if we want to improve ankle stability.

- Knee Flexors are stimulated in the late stance phase and at the beginning of the swing phase, if we wish to increase knee joint flexion, or at heel-on (i.e. the beginning of the stance phase), if we try to improve knee joint stability. In order to prevent knee joint hyperextension, stimulation is triggered in the middle of stance phase.

- Muscle quadriceps is stimulated in the second third of the swing phase and in the first part of the stance phase to facilitate the knee joint extension and a more stable heel-on.

- Muscle Gluteus Mamsimus stimulation begins with the swing phase and ends at 30% of the gait cycle after the beginning of of stance phase.

Quantitatively the gait was evaluated in accordance with two methods. The one is the method of Minimal Square Deviation of Measured Parameters(11) with Respect to the Statistical Pattern of

Normal Gait, eqation 1 :

$$\min_{j\in J} d_{jk} = \left[\sum_{i=1}^{n} z_{ij}^{2}\right]^{1/2} \quad ; \quad k = Z,P$$

$$z_{ij} = \frac{Y_i - X_{ijk}}{\sigma_i} \qquad (1)$$

where Z_{ij} is a normalized variable expressed in standard units. The index $j\in J$ presents the applied orthosis or the stimulation sequences, and k=Z,P denotes variables of the healthy (Z) and the injured(P) side respectively. The following variables were used in equation 1 :

- step length
- step duration
- stance phase / stride duration
- maximal value of hip flexion in swing phase
- maximal value of knee flexion in swing phase
- aximal value of ankle flexion in swing phase
- time of maximal hip flexion
- time of maximal knee flexion
- time of maximal ankle flexion

The second method is that of Symmetry Deviation Between Left and Right side Gait Parameters, equation 3(20).
The symmetry S is defined as a set of partial symmetries S_i for variables x_i as $S = \{S_i\}$, and the partial symmetry is defined as :

$$S_i = \frac{1}{m}\sum_{k=1}^{m} \frac{X_{iL}}{X_{iR}}(k) \qquad i=1, \ldots r \qquad (2)$$

where m is the number of steps. For the ideal gait $S_i=1$, for normal gait $S_i \doteq 1$, and for pathological gait $S_i \neq 1$. The integral symmetry IS_j is then :

$$IS_j = 1 - \frac{1}{n}\sum_{i=1}^{n} \text{abs}\,(1-S_{ij})\,W_{ij} \quad ; \; S_{ij} > 0 \qquad (3)$$

The subscript i denotes the measured variables and $j\in J$ the applied stimulation sequence. In the equation 3 W_{ij} represents the weighing factor defined as $W_{ij} = 1 + \sigma_{ij} / S_{ij}$ where σ_{ij} is the standard deviation of symmetry S_{ij}.

Results

Table 1 shows kinesiologic clinical analysis of gait for both patients. With the patient Z.J. the analysis is done only at peroneal stimulation. By Y the presence of naomaly is indicated. With the patient V.J. the analysis is done at multi-channel stimulation (Fig.6). The degree of anomaly is progressively measured according to scale where 3 means severe anomaly, 2 moderate anomaly, and 1 mild anomaly. It is evident from the Table which anomalies were corrected by stimulation.

Figure 1 illustrates goniographic and basographic recordings of gait functions in patient Z.J. in conditions without stimulation. Figure 2 illustrates the gait of the same patient with applied stimulation of the pretibial group, m. triceps surae and m. quadriceps. It is evident that the goniogram of the ankle of the affected (right) leg was well corrected, for it narrowly approaches the goniogram of the normal leg. This was realized by coordinate stimulation of ankle antagonists. Because of spasticity

Table 1

Gait Analysis Form

a - Z.J. Hemip. dex. m. 54 years x - without stimulation
b - V.J. Hemip. sin. m. 52 years xx - with stimulation

		x	xx	x	xx
SWING PHASE		a		b	
Hip	Circumducts	Y	Y	1	1
	Externally rotates	Y	Y	2	1
Knee	Inadequate flexion	Y	Y	2	1
Ankle	In varus	Y	-	2	-
	In equinus	Y	-	2	-
REACH					
Pelvis	Lacks rotation	Y	Y	1	1
Knee	Lacks extension			2	1
Ankle	In equinus	Y	-	2	-
STANCE PHASE					
Trunk	Inadequate weight shift	Y	Y	2	1
Hip	Extreme adduction			-	-
	Internally rotates			1	1
	Externally rotates			-	-
Knee	Hyperextends			1	1
	Excessive flexion			-	-
	Unstable knee			2	1
Ankle	Floor contact				
	Lands on lateral border	Y	-	2	-
	Mid stance				
	Dorsiflexion			-	-
	Plantar flexion			1	1
	No push off			2	1

of m. quadriceps no improvement in the correction of knee flexion was acheived. Yet a slight correction of hip flexion was noticed. Figure 3 shows the improvement of the criterion of integral symmetry at successive addition of stimulation channels, attaining at its maximal value at stimulation sequence shown in Figure 2. A single value of criterion of integral symmetry defined by equation 3 was measured on the pattern of 120 steps. The improvement of integral symmetry from 0.88 at the gait without stimulation to 0.96 at the gait with stimulation

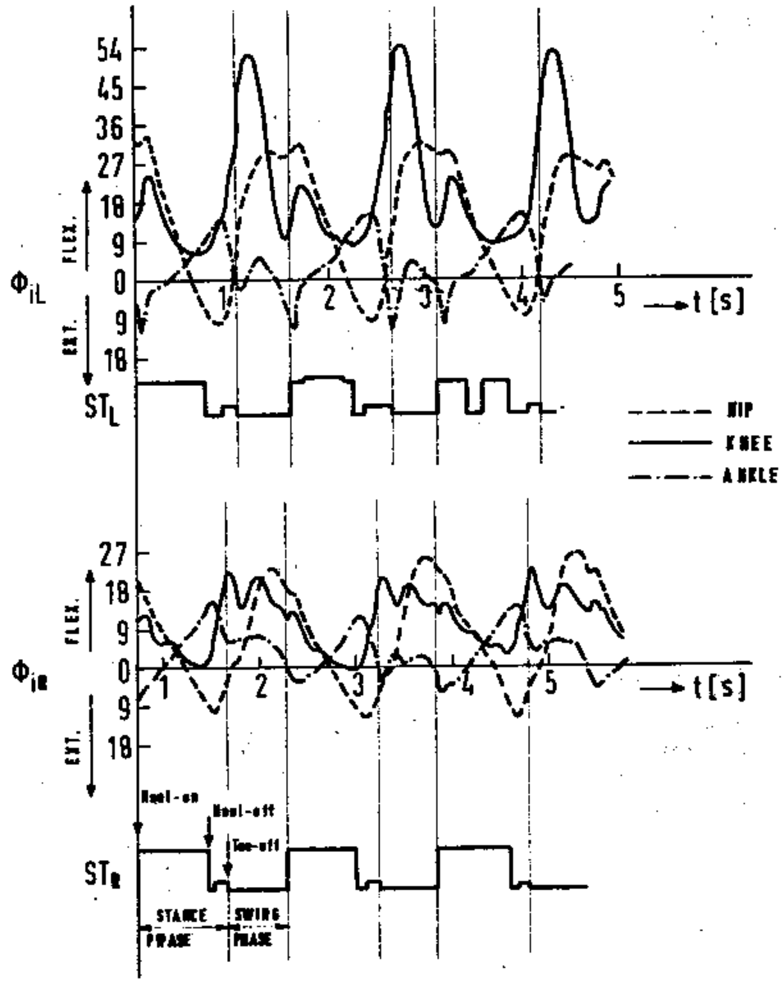

Figure 1 : The Gait Without Stimulation (Z.J. half period time shift)

of pretibal group, m. triceps surae, and m. quadriceps is highly significant (at the level 0.01 ; t=4.39 , $t_{.99}$ =3.75). This sequence is optimal for patient Z.J. With additional stimulation of m. hamstrings knee flexion was indeed increased, yet the integ= ral symmetry dropped to o.91. No therapeutic effect could be seen after that stimulation. The factor of integral symmetry at the gait after stimulation in relation to the gait before stimulation changed nonsignificantly to the value of 0.89.

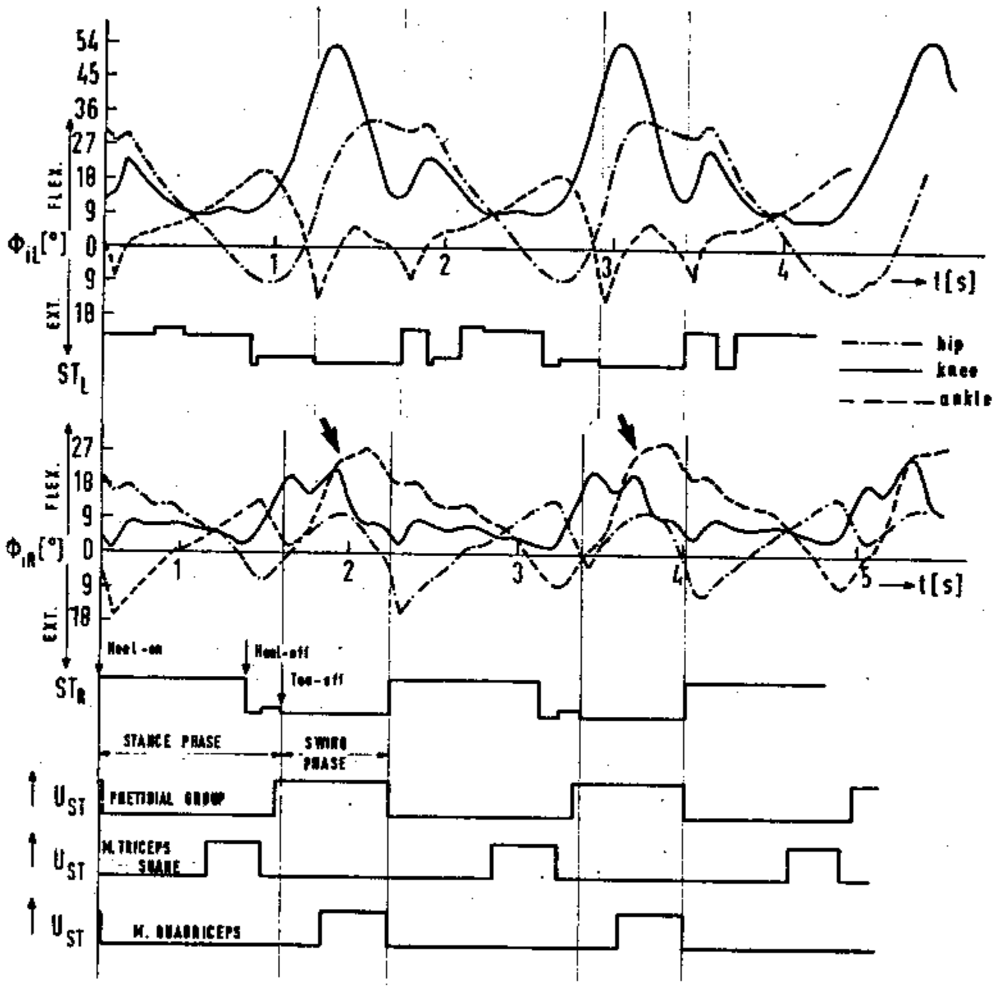

Figure 2 : The Gait at the Stimulation of Pretibial Group, M.Triceps Surae, and M. Quadriceps (Z.J. half period time shift)

Figure 4 shows the course of criterion dkj by which the deviation between patient gait pattern and normal gait pattern is measured (equation 1). The criterion djk has the smallest value for the impared leg at the same stimulation sequence where the criterion of integral symmetry attains at its maximum. We can notice also the increasing of of the criterion djk for the impared leg because of the slowing down of the gait. This means it deviates from normal gait pattern. So, a number of improvements must have appeared

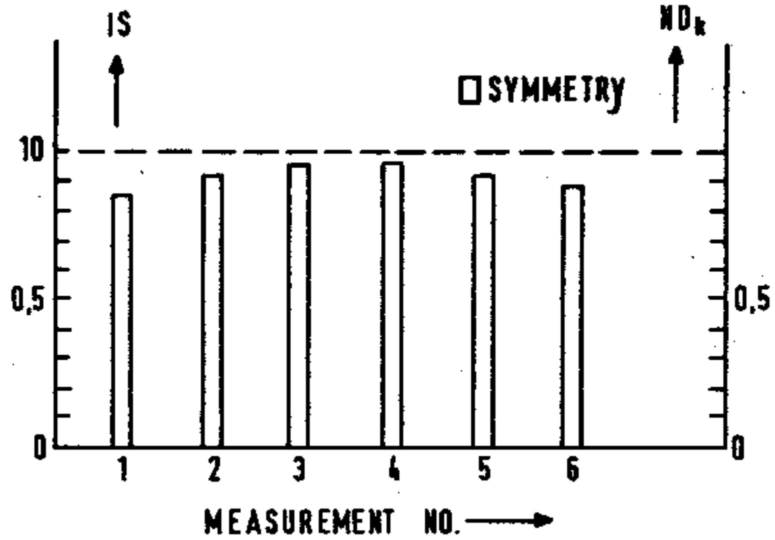

Figure 3 : The Integral Symmetry as a Function of Different Stimulation Sequences (patient Z. J.)

with the impared leg in the rest of parameters, for the criterion djk remains more or less constant at different stimulation sequences.

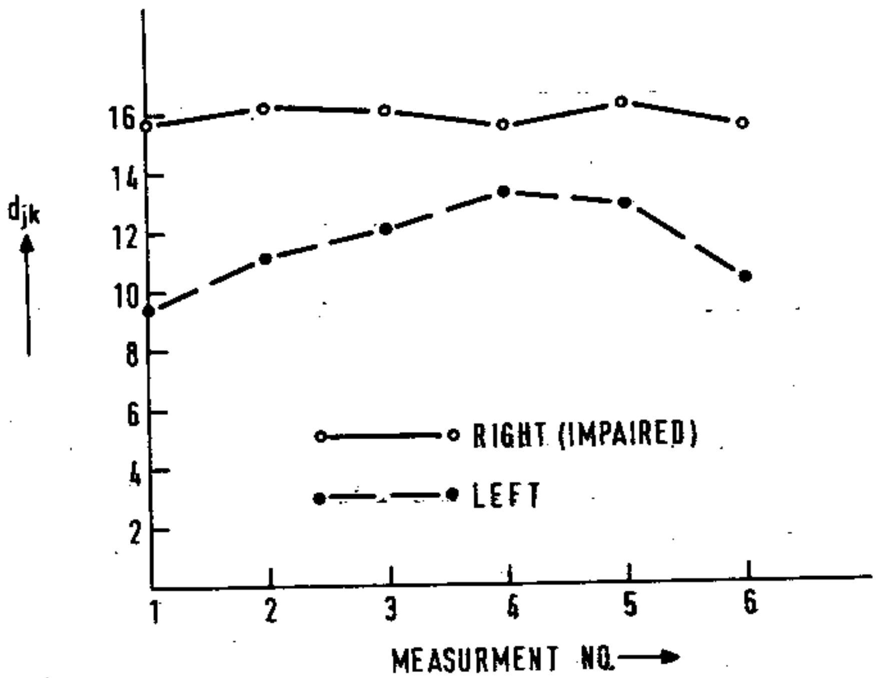

Figure 4 : Criterion djk (difference between normal and measured gait parameters) as a Function of Different Stimulation Sequences (pat.Z.J.)

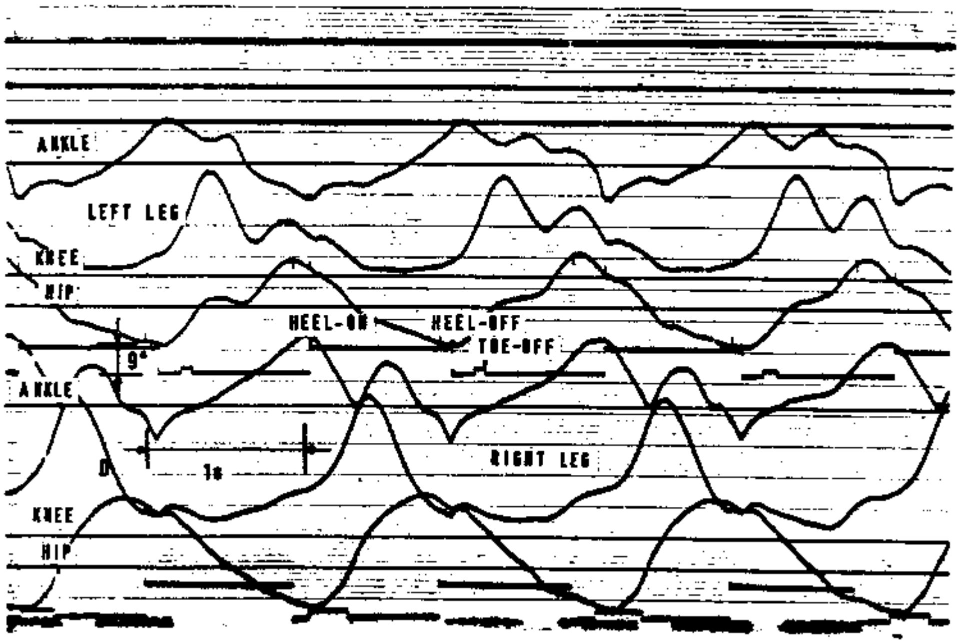

Figure 5 : Gait Without Stimulation (patient V.J.)

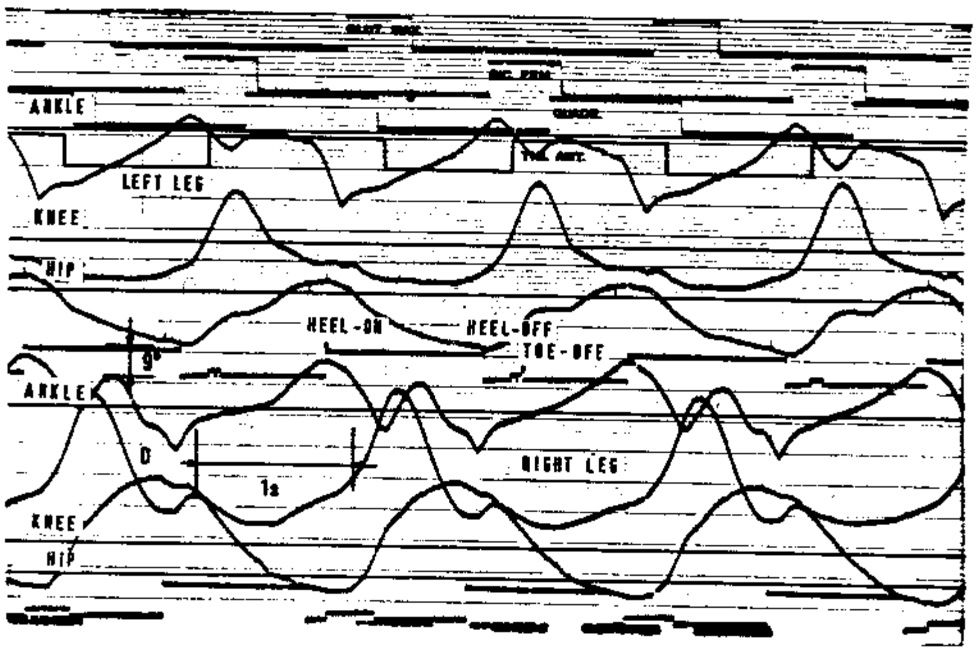

Figure 6 : Gait at the Stimulation of Pretibial Group, M.Hamstrings, M. Quadriceps and M. Gluteus Maximus (patient V.J.)

Figure 5 illustrates goniographic and basographic record= ings of gait functions in patient V.J. without stimulation. The goniogram of the ankle joint taken in the swing phase indicates the tendency towards equinus and has no plantar flexion indica = ted in the heel-off. The pattern is variable. In the goniogram of the ankle joint, two peaks of flexion can be observed in the swing phase as the result of deficiency of m. quadriceps function. Generally speaking, the maximum knee joint flexion is approxima= tely 10 smaller than that of unaffected side. In the middle of the stance phase a slight hyperextension can be noticed. The go= niogram of the hip joint does not show any marked difference in flexion amplitude, except for a couple of peaks appearing from time to time. As far as the amplitude is concerned, no difference between the affected and unaffected lower extremity is noticed. Comparison of the two basographic functions shows that the stance phase of the uneffected extremity is longer than that of the affected extremity.

Figure 6 shows goniograms , foot-switch functions and en= velopes of stimulation pulses during the stimulation of the pretibial group, m. hamstrings, m. quadriceps, m. gluteus maxi= mus. The goniogram of the ankle joint of the affected leg is quite similar to the goniogram of the unaffected leg. Dorsal flexion during the swing phase is obvious, and plantar flexion at heel-off is indicated. The goniogram of the knee joint clear= ly shows maximum flexion at the beginning of swing phase, which makes it extremely similar to the goniogram of the normal knee joint, except for a somehow lower maximum flexion. The gonio= ram of the hip joint indicates a somewhat more rounded course of flexion. Table 1 presents other corrections of gait at this stimulation, too. The value of integral symmetry of stimulated gait compared with the value of integral symmetry of non-sti= mulated gait (Figure 6) is highly significant. This stimulation sequence is optimal for the patient V. J. The factor of inte= gral symmetry at the gait after stimulation does not change sig= nificantly if compared with the beginning gait without stimula= tion.

Conclusion

In this study it has been shown that it is possible to ap= proach hemiplegic gait very narrowly to normal gait pattern by the help of optimal stimulation sequence. The gait correction has been evaluated by qualitative kinesiologic clinical analysis and by two mathematical quantitative criteria , which have shown to be sensitive and selective enough. With the three methods the same stimulation sequences have proved to be optimal, with which also the correctness of mathematical evaluative criteria has been proved.

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