MULTICHANNEL STIMULATION OF LOWER EXTREMITIES

U. Stanič[1], R. Acimović–Janežič[2], N. Gros[2], A. Trnkoczy[1], M. Kljajić[1], T. Bajd[3], J. Krajnik[1], M. Stopar[1]

From [1]J.Stefan Institute, University of Ljubljana, [2]Institute for Rehabilitation of Disabled, Ljubljana, [3]Faculty of Electrical Engineering, University of Ljubljana, 61000 Ljubljana, Yugoslavia

Introduction

In 1961 first electronic peroneal brace was described (1) and later till 1970 already several devices have been developed and successfully applied (2,3,4,5,6). This induced the research of multichannel stimulation (7,8) in 1970. Later on in 1974 the research of optimal stimulation sequences was initiated and partial results were obtained (9,10). The continuation of this work resulted in more concise methodology of application, general rules of stimulation sequences determination, new hardware development and data concerning the instantaneous effects of stimulation in correction of hemiparetic gait pattern (11).

The purpose of this paper is to summarize our experience on application of multichannel stimulation for correction of hemiplegic gait obtained in last few years. Furthermore to give an estimation how close we approach to the main rehabilitation goals. Our intention has been to enable the patients a more normal, comfortable and repeatable walking with less futiguing. This encreases the level of their autonomy.

Methodology

The methodology of multichannel stimulation of paretic lower extremities application consists of patient selection, determination of electrodes sites and stimulation parameters, selection of stimulated muscle groups and determination of adequate stimulation sequences and timing of the stimulation therapy. As this detailed data is presented in paper (11) here only a short information is given on stimulation sequence determination and role of main leg muscle group stimulation to avoid anomalies.

The research of the effects of multichannel stimulation on correction of hemi-

plegic gait pattern is based on experiments. The effects of stimulation are estimated qualitatively by clinical gait evaluation method (10) and quantitatively by gait evaluation methods based on measurements of the symmetry of step time and stance phase time (17).

The determination of stimulation sequences, i.e. which muscles are to be stimulated and when the stimulation of individual muscles is to occur during the gait cycle to correct abnormal gait, is made in a sequential way. First the initial stimulation sequence is chosen and then it is altered by a trial and error procedure to obtain the best gait correction.

The initial stimulation sequence for each patient is determined individually, based on clinical analysis of gait the aim being to eliminate or diminish the patients anomalies.

In spite of the fact that the selection of muscle groups and the timing of the stimulation are individual for each patient, some general rules for correction of anomalies have been established in the course of time.

The pretibial muscle group is stimulated in the case of extension gait pattern from the terminal stance phase throughout swing phase to the loading response. In the case of a flexion pattern, stimulation is superfluours or must be terminated at the time of landing. By stimulation, equinus and varus are corrected and proper initial contact promoted. The stimulation also releases active clawing of the toes. For this purpose, in one case the extensor hallucis longus was also stimulated. Usually, applying multichannel stimulation, we first stimulate the pretibial muscle group to achieve clearance of the foot and proper landing on the heel, which promoted reliable triggering of the stimulator by the heel switch.

M. soleus is stimulated in terminal stance and pre-swing phase to enable active push-off without affecting the flexion of the knee.

M. gastrocnemius, which, unlike the soleus, is a two joint muscle, is stimulated from the loading response to the midstance phase, by which the knee joint motion is stabilized and also helps in prevention of hyperextension.

The knee flexors are stimulated from terminal swing phase until terminal stance phase in order to prevent hyperextension. By stimulation in the pre-swing and initial swing, insufficient knee flexion can also be corrected.

The knee extensors are stimulated in mid-swing and terminal swing phase to extend the knee joint and in stance phase to enable a better weight shift on the affected leg and limit excessive flexion of the knee. In the case of hyperextension, stimulation of the knee extensors in stance phase is omitted so as not to spoil the correction obtained by m. gastrocnemius and knee flexor stimulation.

The hip extensors are stimulated in terminal swing phase to deaccelerate

the swinging leg, then in stance phase to enable a more normal weight shift, and in the mid-stance phase for stabilization of the pelvis.

The hip abductors are stimulated in the stance phase to correct pelvis drop and in the swing phase to prevent adduction of the leg.

Instrumentation

In the experiments two versions of six channel stimulators were used. At the beggining the analog version with rotary potentiometers for adjustment of stimulation sequences (12) and during last two years the digital six-channel stimulator with graphical representation of stimulation sequences (13) were applied. Both stimulators are clinically oriented and were designed for therapeutic use. Here only the digital version is described, Fig. 1.

Fig. 1. The digital six-channel stimulator applied to hemiplegic patient

The stimulator has four full–channels (for the entire stride time) and two half–channels which can be used for swing or stance phase, or can be combined into one (fifth) full–channel.

The stimulation program is triggered for swing and stance phase separately by heel–off and heel–on events via a heel switch mounted in the shoe insole under the impaired leg. In comparison with analog version of stimulator (12) the digital one has several advantages. Besides a fixed regime, a walking rate dependent duration of stimulation sequences is possible, which enables a free choice of gait cadence by the patient. The duration of all stimulations is changed proportionally to the gait cadence. Self–adapting stimulator allow the patient to choose his optimal gait cadence and to decrease energy consumption during walking (14). Graphical representation of the stimulation sequence set is of utmost importance for easy adjustment and alteration of the stimulation program by medical personnel. Compared to analog version (12), the graphical representation is efficiently improved by representing stride time with 16 discrete time intervals. In each of them the stimulation of preditermined amplitude (which can be set by six rotary potentiometers) is turned–on by a separate switch. In this way nearly linear representation of stimulation in time is achieved. This allows good control and facilitates the synthesis of stimulation sequences by a doctor or PT. At first sight, 16 discrete intervals for one stride time might seem too inexact a control but till now no requirement for finer control was noticed. Another advantage of switch control is that stimulation can appear twice during a stride period. In course of experiments several types of surface electrodes have been used (11).

In parallel with the clinical analysis of gait, we tried to objectify statistically the influence of multichannel stimulation on the gait by measurements of goniograms in the sagittal plane and basograms for both legs. Suitable instrumentation for this purpose is a light goniometric system in combination with proccess computer that enables on–line data processing and computing of quantitative criterion (15,16).

Results and discussion

The research of instantaneous effects of multichannel stimulation has been completed on eleven patients (11).

In Figure 2 the results of clinical analysis of gait anomalies are shown (graded in three degrees: 3–severe, 2–medium, 1–minor and 0–no anomaly). The white bars present the average degree of initial anomalies for treated patient population and the black bars present the average degree of remaining anomalies during multichannel stimulation.

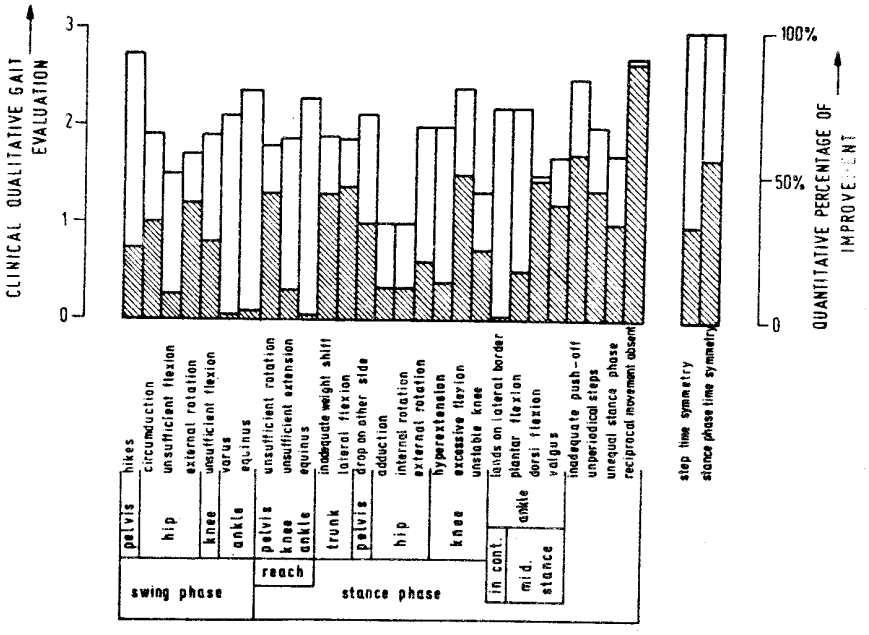

Fig. 2. Instantaneous effects of multichannel stimulation evaluated by clinical gait evaluation method and by measurement of gait symmetry

The stimulation is most efficient for correction of equinus, varus, and for the correction of landing on the lateral border of the foot, because these anomalies were eliminated (100 %) with all patients treated. A very high efficiency is also shown in the case of hip flexion in the swing phase (83 %), but this must be accepted with reserve because the data only relate to four patients. Further, stimulation is very efficient for the correction of knee extension in the swing phase (84 %), of knee hyperextension (81 %), external rotation of the hip in stance phase (75 %), plantar flexion of the ankle in stance phase (75 %), circumduction of hip (70 %), hikes (63 %), insufficient knee flexion in swing phase (58 %), pelvis drop on other side (53 %), unstable knee (50 %), etc. it can be seen that stimulation is somewhat less successful in the stance phase than in the swing phase. For the

purpose of correction of weight shift it amounts to 32 %, of excessive knee flexion 40 %, of push—off 32 %. The reason for the relatively lower efficiency of stimulation in the stance phase is the circumstance that this phase is subject to higher external loads that cannot be fully compensated by surface stimulation and rectangular envelopes.

Greater effectiveness of stimulation in swing phase is confirmed also by the change in symmetry factors as the step time symmetry improvement is significant for 67 % and with stance phase time only 44 % of the patients.

In the study of therapeutic and/or long term effects till now six patients have completed the program (the complete number of patients is planned to be twenty, ten in stimulated and ten in control group). In the paper only partial results are given based on the results of clinical gait analysis. In Figure 3 the sum of graded anomalies as a function of time with each individual patient is given. The sum of 15 would mean minor, 30 medium and over 40 severe impairness. In the stimulated group there were three patient trained from beginning by 6—channel stimulation 3 to 4—times a week, 10 to 80 minutes a session, in the control group there were three patients involved in regular program without stimulation. From the comparison of both groups it is evident that till now no significant difference in rehabilitation progress can be observed in stimulated group compared to unstimulated. Naturally, at present the sample is to small to give any final judgement. But it is evident that 6—channel stimulation instantly drastically lessens the sum of anomalies what had been shown already before.

It is known that with hemiparetics the inconsistent pathological muscular activity is manifested also in greater variability of gait parameters then with normals (14). This effect is more noticeable in the swing phase, while in the stance phase it is concealed by strong external moments. It was observed (11) that multichannel stimulation noticeably reduces variability of goniograms of the impaired side. The explanation for this effect is that by the stimulation sequences besides power input also certain information input influences the locomotor systems (18). In Fig. 4 the goniometric functions entropy (logarithm of the probability for a certain interval of goniograms) in conditions with and without 6-channel stimulation at comfortable gait speed is shown (18). The entropy was computed from hip, knee and ankle goniograms samples at the time when the knee goniogram reaches its maximal flexion during the swing phase. The reduction of entropy for the impaired leg and swing phase is appearent. As it was shown (14,18) that lower entropy of the system at free gait cadence correlates to lower energy consumption it means that multichannel stimulation lessens also the futiguing of the patients during walking. In practice this is reflected in longer ability of walking with multichannel stimulator.

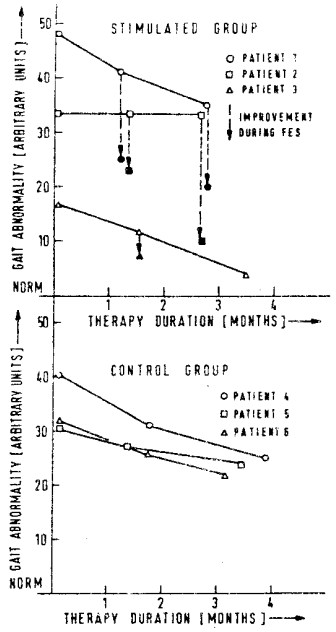

Fig. 3. Control study of therapeutic effects with 6-channel stimulation of paretic lower extremities – partial results

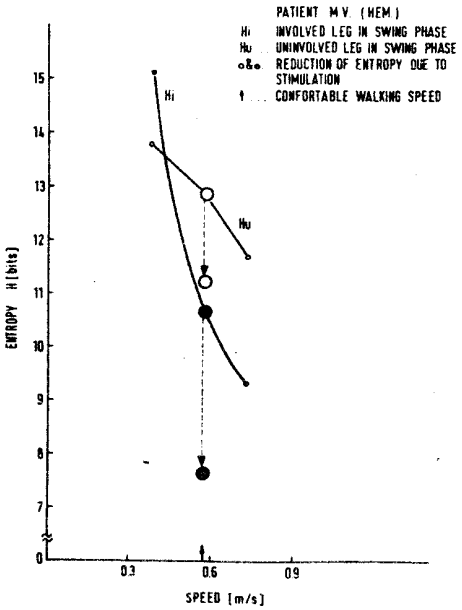

Fig. 4. Entropy of goniometric function of hemiplegic patient versus velocity without stimulation and with multichannel stimulation at free gait velocity

Conclusion

In the paper it is shown that the application of multichannel stimulation to hemiparetic patients effectivelly corrects most of their typical gait anomalies. The multichannel stimulation causes also the reduction of goniogram entropy what correlates with lower energy consumption during walking. All those facts speak in favour of the multichannel stimulation as it normalizes the patients gait, makes it more comfortable reliable and repeatable. The developed methodology of application and new versatile stimulator significantly contribute that the method could be more easily accepted in rehabilitation centers. The control study of possible therapeutic effects has not been completed yet but from the data gathered, there is no indications for existence of such effects. Therefore orthotic use of multichannel stimulation appear to be more promising. It is still not answered to which extend multichannel stimulators could be used as orthotic devices but there is no doubt that implanted electrodes and better control principles will significantly promote such intention.

Acknowledgement

This work was performed with the assistance of the Rehabilitation Institute, Ljubljana, Department for Physical Medicine and Rehabilitation, and has been supported in part by the Slovene Research Community, and in part by Research Grant No. 19-P-58451-F-01 from the Division of International Activities, Rehabilitation Service Administration, Department of Health, Education and Welfare, Washington, D.C. 20201.

References

1. Liberson, W.T., Holmquest, H.I., Scott, D. and Dow, M. (1961), Functional electrotherapy in stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients, Arch.Phys.Med.Rehab. 42, 101.
2. Vodovnik, L., Dimitrijević, M.R., Prevec, T. and Logar, M., (1966), Electronic walking aids for patients with peroneal palsy. World Electron. Instr. 4/2, 58-61.
3. Gračanin, F., Prevec, T., and Trontelj, J. (1967), Evaluation of use of functional electronic peroneal brace in hemiparetic patients. Proceedings of the International Symposium on External Control of Human Extremities, Dubrovnik, 1966, 198–205.
4. McNeal, D., Wilemon, W.K., Mooney, V., Boogs, R. and Tamaki, T. (1969),

The effect of peripheral nerve implanted electrical stimulation on motor control in stroke patients. World Congress of Neurological Sciences, New York.

5. Jeglič, A., Vavken, E. and Benedik, M. (1970), Implantable muscle or nerve stimulator as a part of an electronic brace. International Symposium on External Control of Human Extremities, Dubrovnik, 1969. Advances in External Control of Human Extremities, 593–603.
6. Yergler, W.G., Wilemon, W. and McNeal, D. (1971), An implantable peroneal nerve stimulator to correct equinovarus during walking, J. Bone & Joint Surg. A53, 1660.
7. Kralj, A., Trnkoczy, A., Ačimović, R., Improvement of locomotion in hemiplegic patients with multichannel electrical stimulation; Human locomotor engineering, The Institution of Mechanical Engineers, pp. 45–50, 1974.
8. Milner, M., Human locomotion and possibilities for programmed electrical stimulation of available musculature, S. Afr. Med. J., 46, p. 374, 1972.
9. Stanič, U., Ačimović, R., Bajd, T., Gros, N., Kljajić, M., The use of optimal multichannel stimulation in the correction of hemiplegic gait, Advances in external control of human extremities, Yugoslav committee for electronics and automation, Belgrade, pp. 269–278, 1975.
10. Ačimović, R., Stanič, U., Gros, N., Bajd, T., Correction of hemiplegic gait pattern by multichannel surface stimulation during swing and stance phase, Biomechanics V-A, Intern. Ser. on Biomechanics 1A, Ed.: P.V. Komi, pp. 444–451, 1976.
11. Stanič, U., Ačimović, R., Gros, N., Trnkoczy, A., Bajd, T., Kljajić, M., Multichannel electrical stimulation for correction of hemiplegic gait–methodology and preliminary results, Scandinavian J. of Rehab. Medicine (in print), 1978.
12. Strojnik, P., Kralj, A., Uršič, I., Programmed six-channel electrical stimulator for complex stimulation of leg muscles, IEEE Trans. on Biomed. Engng., 1977, (to be published).
13. Trnkoczy, A., Stanič, U., Maležič, M., Ačimović, R., Gros, N., The development of multichannel FES stimulators for gait correction in paretic patients. 1st Mediterranean Conf. on Med. & Biol. Engng., Sorrento, Italy, Digest of Papers, 1, pp. 1–9 (1977).
14. Kljajić, M., Trnkoczy, A., A study of adaptive control principle orthoses for lower extremities, IEEE Trans. on Systems, Man and Cybernetics, SMC Vol. 8, No. 4, pp. 313–321 (1978).

15. Trnkoczy, A., Bajd, T.: A simple electrogoniometric system and its testing. IEEE Trans. on Biomedical Engineering, BME-22, pp. 257–259, 1975.

16. Bajd, T., Stanič, U., Kljajić, M., Trnkoczy, A.: On-line electrogoniometric gait analysis, Comp. & Biomed. Research, 9, No. 5, pp. 439–444 (1976).

17. Kljajić, M., Bajd, T., Stanič, U.: Quantitative gait evaluation of hemiplegic patients using electrical stimulation orthoses, IEEE Trans. on Biomed. Engng., BME-22, No. 5, pp. 438–441, 1975.

18. Kljajic, M., Stanič, U., Trnkoczy, A.: Energy–information criteria of walking, IVth Int. Congr. Cybernetics and Systems, Amsterdam, August, 1978.