LONG TERM EFFECTS OF MULTICHANNEL STIMULATION ON PATHOLOGICAL GAIT

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ABSTRACT

Long term effects, observed since the invention of FES, has been compared quantitatively in a control study after 2 to 3.5 months of extensive multichannel FES therapy. At the stimulated and at the control group of patients, measurements have been performed before, during, at the conclusion, and 5 to 11 months after the treatment. Measurements at free gait without the stimulation have included step length, gait velocity, ground reaction forces during stance, their distribution under both feet, loading on crutch during gait, goniograms of angles in the six leg joints, as well as EMG recordings from twelve muscle groups included in gait and posture. The previously designed instrumentation has enabled on-line data processing for the most quantitative parameters. Statistical approach to the results of measurements on at least 40 steps of each patient includes graphical representation of the collected data with their mean values and standard deviations. The results have indicated the therapeutic value of multichannel electrical stimulation of gait at the conclusion of the therapy. Comparing with the control group of patients, the recovery rate and the correction level have shown better results with the stimulated group. Some of the anomalies have reappeared partly several months later, mostly at more distal muscle groups, indicating thus the use of simpler orthotic devices in several cases.

INTRODUCTION

Multichannel electrical stimulation of lower extremities was invented as an active rehabilitation method for paretic patients ten years ago (1). It has been proved that the application of cutaneous stimulating electrodes to main muscle groups involved in walking together with the appropriate timing of stimulation can normalize paretic gait significantly (2). Typical gait anomalies estimated by kinesiological analysis are reduced during the stimulation, step length and time are improved, while goniograms of joint angles and forces under both feet are corrected as well. Besides, multichannel electrical stimulation helps establishing initial gait patterns and antigravity support in the early phase of rehabilitation. With the extended multichannel therapy, the recovery rate seems to be faster, correction level higher, and fatiguing of patients lesser than with other therapies.

Post-stimulatory improvements were being observed since the begining of functional electrical stimulation. Results of single channel peroneal stimulation have been discussed on short term (3,4) and long term basis where significant increase of muscle force (5), improvement of motor coordination, gait pattern, and neurological conditions (6) have been reported suggesting short or long term changes in the central nervous system. Besides direct activation of the main leg muscles in correct timing, considerably more compex information input is applied to the afferent nervous pathways ánd transmitted to the higher nervous centers with the intensive multichannel therapy (7,8). With this and with the results of previous reports, considerably larger therapeutic effects have been expected at the conclusion of multichannel therapy (8). The research work on this field has been continuing for three years (9,10) with the purpose to invest igate qualitatively and quantitatively the therapeutic effects of multichannel electrical stimulation as it is now to initiate new directions of research. With sufficient effects of multichannel therapy, only simple orthotic stimulators (11) or even no stimulation would be required after its conclusion. In the opposite case, the design of orthotic multichannel stimulators and methods for their permanent use would be strongly indicated. The present state of multichannel stimulation does not enable its use outside clinical environment successfully.

A control study between stimulated group of 11 patients and non-stimula= ted group of 9 patients has included clinical kinesiological analysis of gait, measurements of main biomechanical parameters of gait and clinical tests. Measurements of additional parameters have been included later to explicit primary investigation.

METHODOLOGY

The stimulated group of patients has been selected considering disabilities, age, initial gait pattern, etc. Since the therapy of every patient has lasted some months, both groups have been formed throughout the control study. At the selec= tion of two similar groups, difficulties have been encountered concerning localisation and extent of the insult as well as restrictions from ethical reasons. Namely, all the patients have had to be given the maximal therapy. Thus, the control group has been selected from patients who refused the stimulation or with whom it has been contraindicated.

Simularity of both groups of patients has been achieved in status after cerebrovascular insult, adequate motivation, period from the insult to the begining of therapy (approximately 5 months), accompanying pathologies (hyper= tension, myocardiopathy etc.), period of therapy. The control study has included 10 hemiplegic patients in the group without stimulation, while the stimulated group has consisted from 10 hemiplegic patients and as a special case 1 paraparetic patient with the lesion on thoracic level Th7 due to barotrauma. There have been 5 left and 5 right side hemiplegic cases in the control group, while 4 left and 6 right side hemiplegic patients have formed the stimulated group.

Both groups of patients have been treated daily for equal amount of time throughout their treatment. Patients in the control group have been involved in regular therapeutic program excluding any kind of electrical stimulation. Patients in the stimulated group have been also partly included in the regular program. Besides, they have been treated by multichannel electrical stimulation five times a week, each stimulation session lasting from 10 minutes at the begining to more than one hour at the conclusion of therapy in several cases. The stimulation period has been adapted to physical condition of each patient individually. The therapy for patients of both control and stimulated group has lasted from approx= imately two to three and half months.

For stimulated patients, adequate multichannel stimulation has been applied according to their disabilities and previously established methodology (2). The stimulation sequences during swing and stance phases of gait have been determined for each patient observing his motoric lacks. Cutaneous electrodes of four, five or six separate channels of stimulation have been applied to pretibial muscles (n. peroneus communis) and plantar flexors (m. soleus mostly) of ankle, knee extensors (m. quadriceps), knee flexors (m. semi= tendinosus, m. semimembranosus, m. biceps femoris), hip extensors (m. gluteus maximus), and hip abductors (m. gluteus medius and minimus) respec= tively. In some cases with sufficient hip abduction during stance phase, one of the channels have been used for extension of elbow (m. triceps brachii) to evoke the reciprocal movement of arm during swing phase (12).

For the paraparetic patient with the main motoric deficit on the right side, new stimulation sequences have been determined and eight channel stimulation applied to left and right hip extensors, right hip abductors, right knee flexors, right plantar flexors, and left and right pretibial muscles (13).

The rehabilitation therapy has been accompanied with tests and measure= ments throughout its duration. Initial tests and measurements were performed before its begining. For both groups, all the tests and measurements have been accomplished at free gait without stimulation. Only so the changes due to the rehabilitation can be compared between both groups and patients can be observed from cybernetic aspects as dynamic systems enabled by the therapy without side-effects (7,8,14). Five to eleven months after the tests and measurements at the conclusion of the therapy, another control tests and measurements have been carried out to record possible therapeutic effects after an extensive period of time. There, several influences beside the therapy have been expected and encountered as well.

For each patient, test of motor functions and clinical kinesiological analysis of gait have been fulfilled grading anomalies at leg joints and body from 1 to 3 during several parts of swing and stance phase (15). Average step length and average velocity of gait have been measured for basic comparison, both parameters being important biomechanically for the final intent of locomotion. Average diagrams of ground reaction forces and their spatial distribution under the feet during stance phases have been measured together with average loading on crutch when used (16). Average goniograms of the six leg joints have been added in the course of investigation as well as surface EMG recordings from six muscle groups involved in gait and posture on each side to objectify measure= ments of external biomechanical parameters.

INSTRUMENTATION

Two clinical and research oriented six channel digital stimulators have been used in the stimulation therapy (17). Channels of both stimulators can be programmed by arrays of switches whose position graphically represent the stimulation sequences in addition. Separate independent channels are triggered by a single heel-switch in the shoe of the impaired leg. Optionally, two switches under both heels can be applied with the later developed stimulator triggering three channels each. This has proved useful with the paraparetic patient where besides, the electrodes on hip extensors and on hip abductors have been connected in parallel to one channel and a small orthotic stimulator attached under the patien's knee (11) has been applied to one of the peroneal nerves. All the stimulators adapt themselves to the walking rate of the patient (14).

Ground reaction forces and their distribution under the feet during stance phases have been computed with a system of shoes containing 8 force trans= ducers each, amplifiers, and program implemented on miniprocessor (18). Similar system with the force trasducer in crutch has been used for on-line measurements of crutch loading. Lightweight goniometric system (19), combined with the force-shoes instead of commonly used foot-switches and refined with new software, has processed joint angles in the sagital plane when applied (20) together with the ground reaction forces. The whole system is connected together by cables. EMG recordings have been registered by silver cutaneous electrodes, telemetry, and a standard polyelectromyograph.

RESULTS

Average step length $\bar{L}$ (in meters) and average velocity of gait $\bar{V}$ (m/s) as functions of time (months) are given for 11 patients in the stimulated group (Fig. 1 and 3)and for 10 patients in the control group (Fig. 2 and 4). Each point on the diagrams contains 3 courses of 14 to 30 steps where both length and time have been measured and devided by the number of steps. Time axes of the four diagrams are interrupted at the conclusion of therapy (dashed vertical lines) and shortened after it. Continuations of curves to the points of control measure= ments 5 to 11 months after the conclusion of therapy are steepened by shorter time axes and can not be compared only as the effects of therapy. Besides it, they are pictures of psycho-somatic statuses of patients, their home environ= ments, their occupations, motivations, etc.

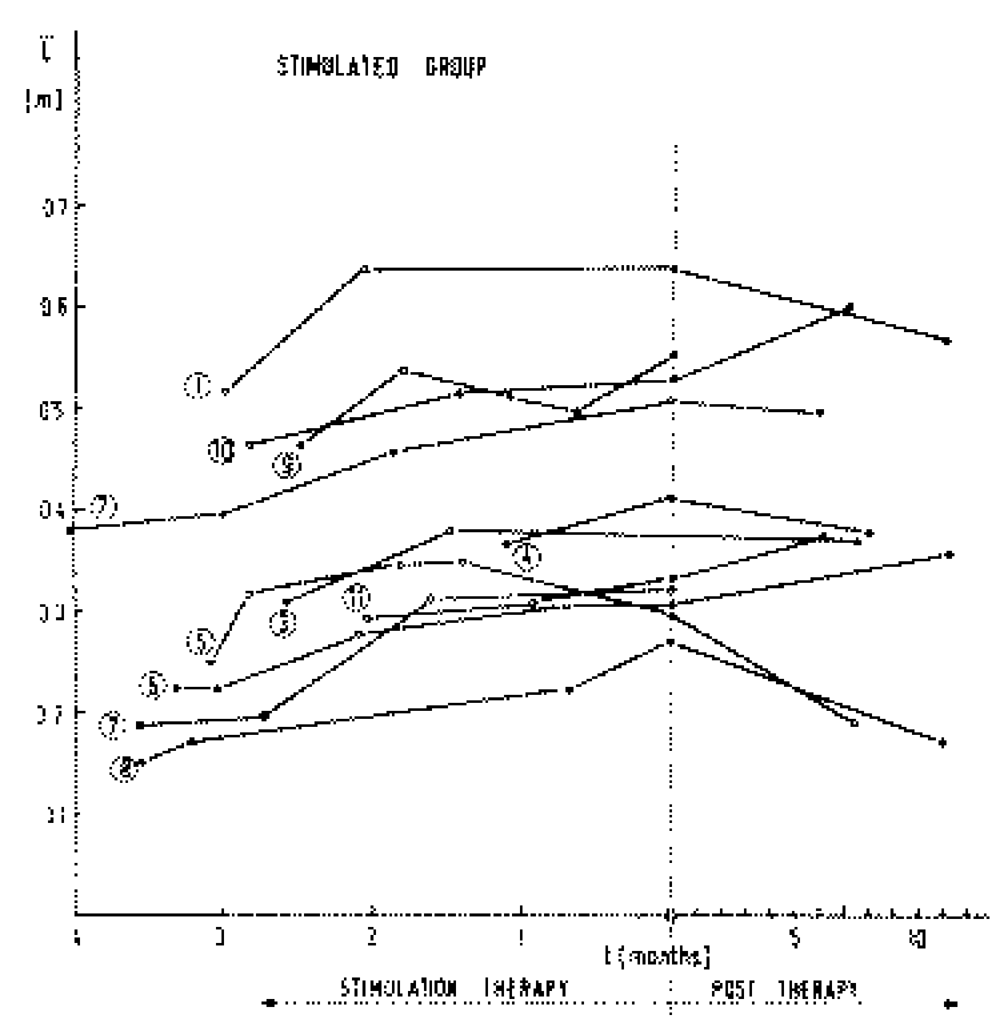

Fig. 1. Average step length, stimulated group of patients.

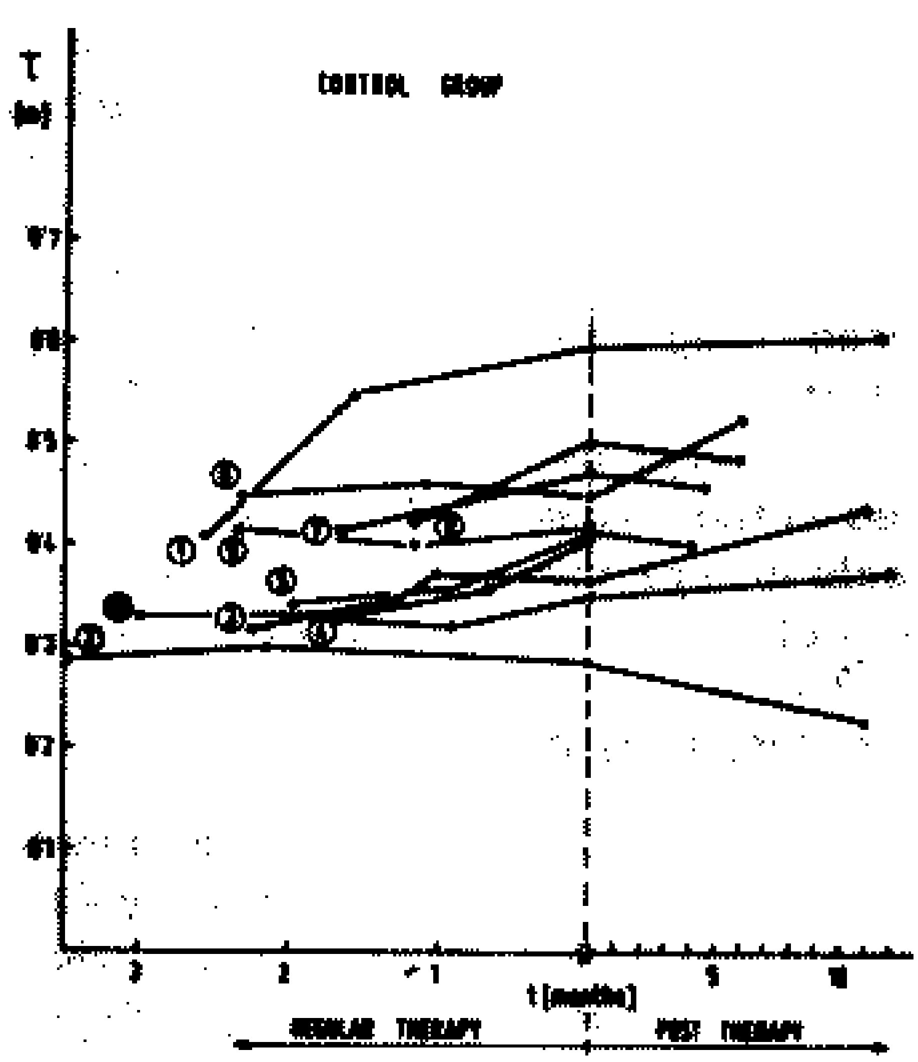

Fig. 2. Average step length, control group of patients.

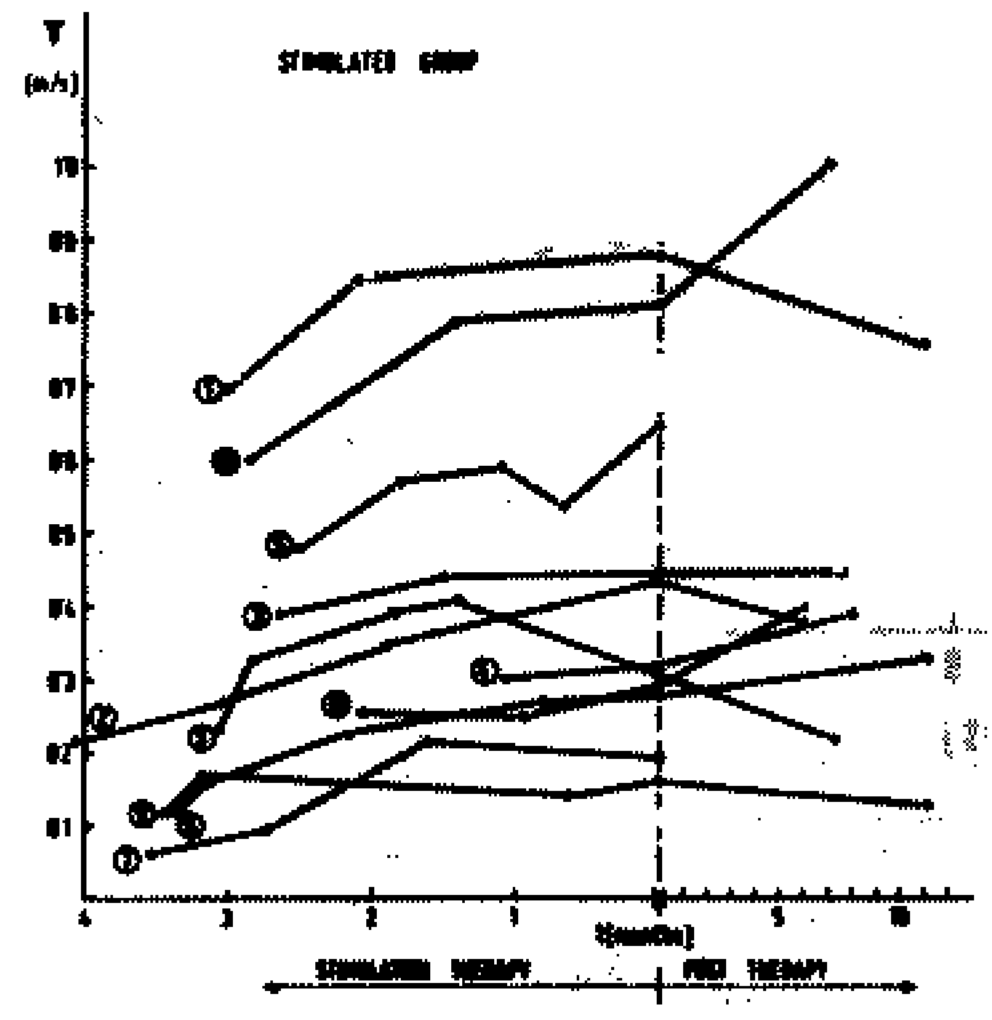

Fig. 3. Average velocity of gait, stimulated group of patients.

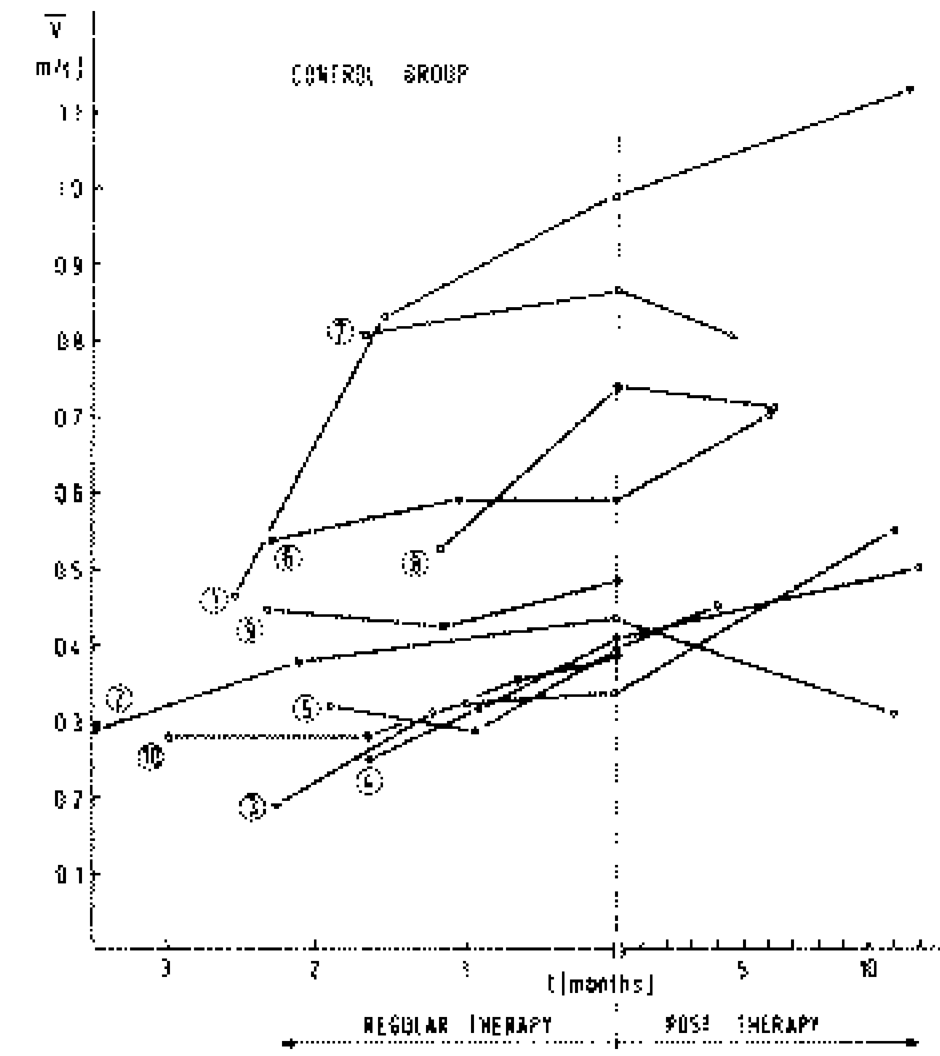

Fig. 4. Average velocity of gait, control group of patients.

During the therapy, the majority of curves roughly approaches an expected exponential improvement of both parameters:

$$\overline{L} = \overline{L}_1 + (\overline{L}_0 - \overline{L}_1).(1 - e^{-a(t).t}) \quad \text{and} \quad \overline{V} = \overline{V}_1 + (\overline{V}_0 - \overline{V}_1).(1 - e^{-b(t).t})$$

where index 1 represents the initial value before the therapy, index 0 the limiting value approaching to the one before the insult (7,14), while a and b cover the effectiveness of therapy, psycho-physical condition of the patient, his motivation, etc. and are changing with time.

Average curves for both groups could hardly be computed and interpreted statistically due to small number of patients and large differences among them hidden both in the initial values $\overline{L}_1$ and $\overline{V}_1$ as well as in the coefficients a and b. Diagrams of mean values of the average step lengths and the average velocities of gait for the first nine patients from both groups have been normalised to their mean initial values $\overline{L}_1$ and $\overline{V}_1$ and do not represent large populations of patients (Fig. 5 and 6). They may only serve for comparison between these two groups.

Average step length $\overline{L}$ has increased considerably more with the stimulated group than with the control one during the therapy, corresponding with results of kinesiological analysis of gait where an effective correction of the anomalies have been shown due to the stimulation of proximal muscle groups (Fig. 7). $\overline{L}$ has decreased slowly during the post-therapeutic period, when it has been still increasing slowly at the control group. The values of both stimulated and control group have been approaching approximately the same limit one year after the therapy.

Average velocity of gait $\overline{V}$ has reached similar values for both groups at the end of therapy. During the post-therapeutic period, $\overline{V}$ has remained

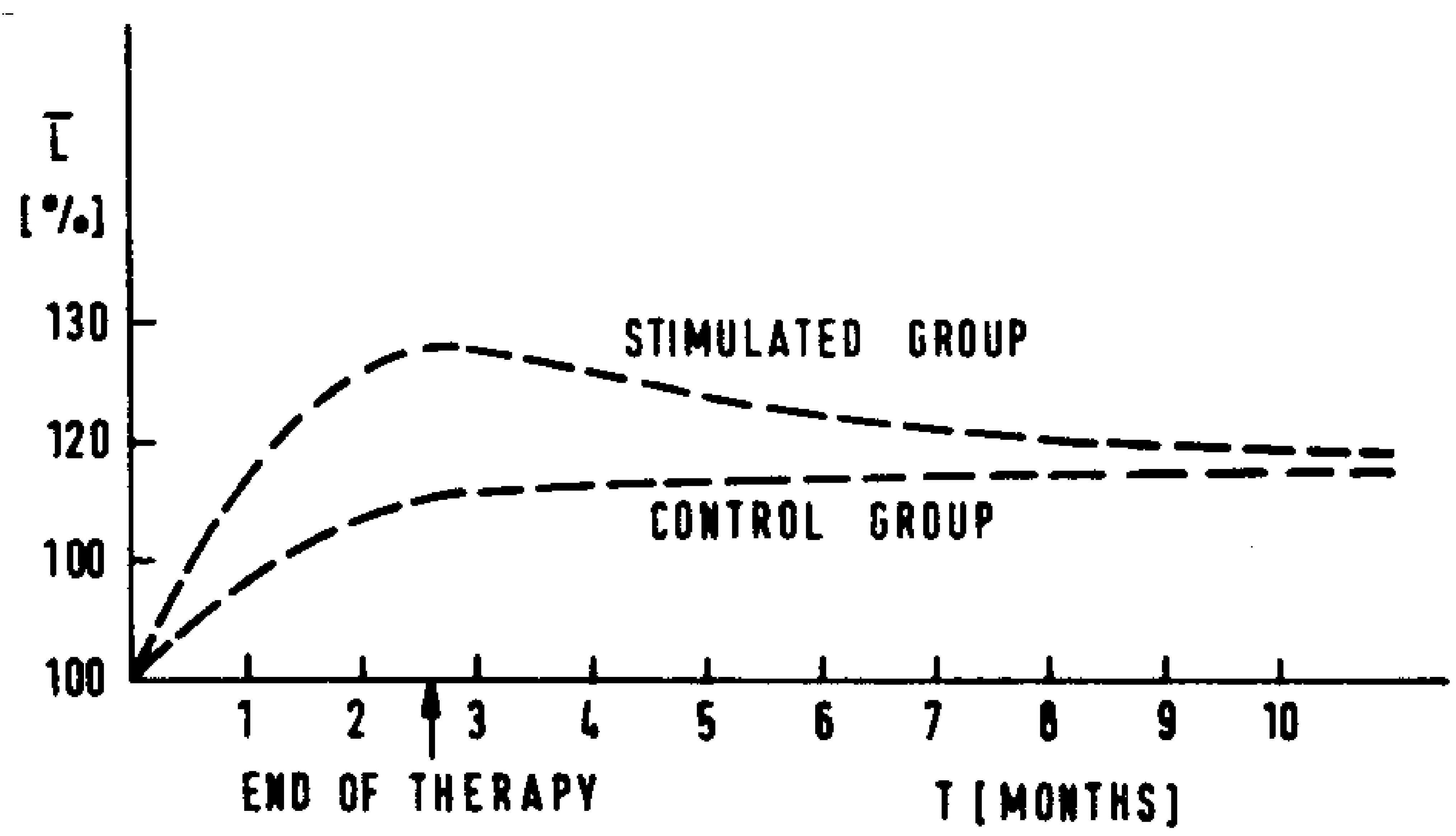

Fig. 5.

Normalised mean values of the average step length.

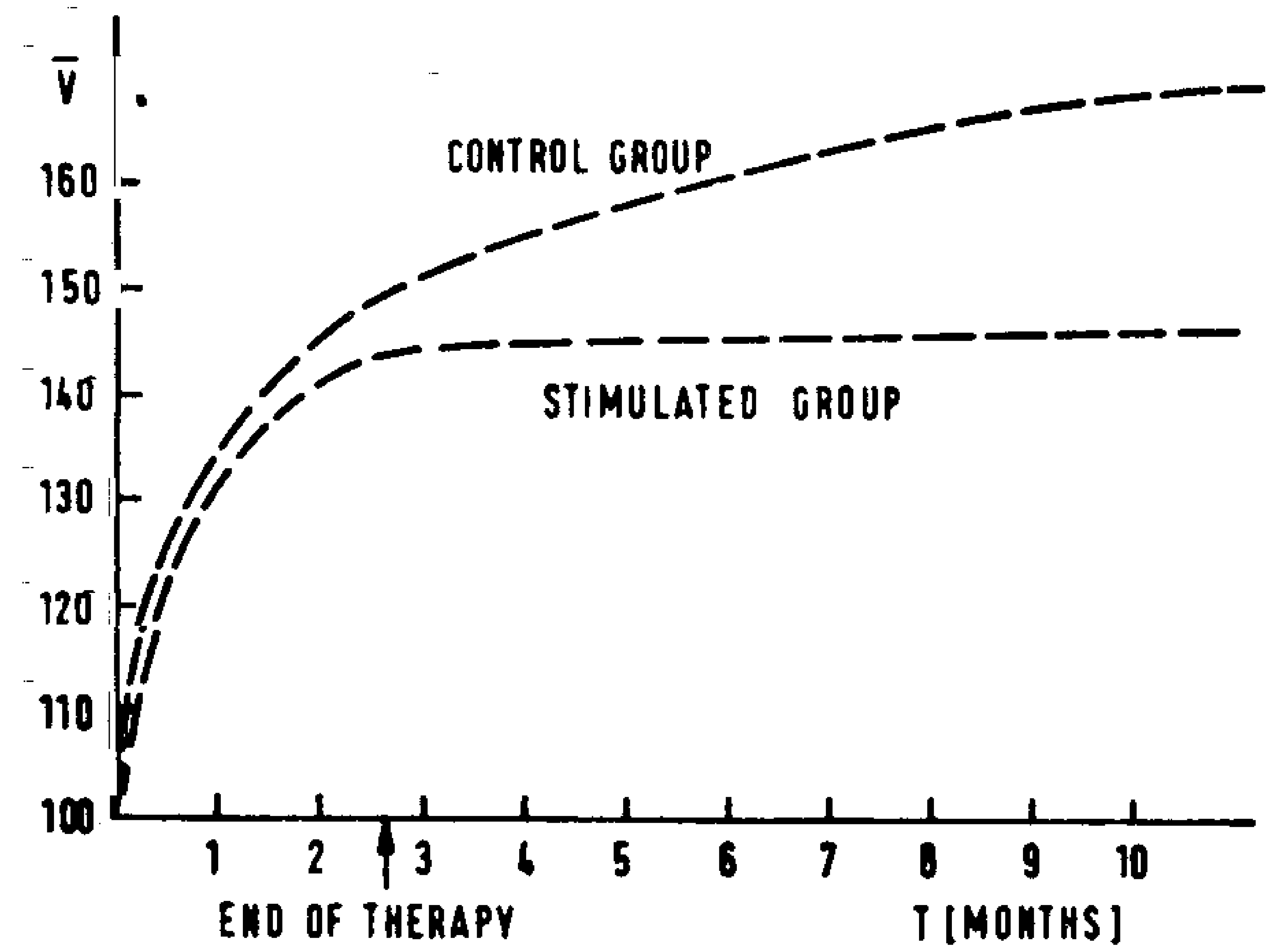

Fig. 6.

Normalised mean values of the average velocity of gait.

approximately the same at the stimulated group, while it has been still increasing at the control one. For the stimulated group, both diagrams have reached either their highest point or the saturation at the conclusion of therapy, while both the average step length and the average velocity of gait have been still increasing during the post-therapeutic period for the control group. Considering the gradients of curves and the lower starting points of both parameters at the stimulated group of patients (Fig. 1 to 4) as well as larger anomalies at kine= siological analysis of gait (Fig. 7), the multichannel electrical stimulation has rehabilitated the patients faster than the standard therapy. However, its thera= peutic effects have been slowly fading during post-stimulatory period.

Clinical kinesiological analysis of gait has included 55 observations of anomalies at leg joints, posture and symetry during several parts of swing and stance phase rating anomalies from 1 to 3 where observed (15). Ratings of anomalies have been gathered to 14 parts for trunk, pelvis, hip, knee, and foot during swing, loading, stance, and push-off phases of gait. The analysis has been

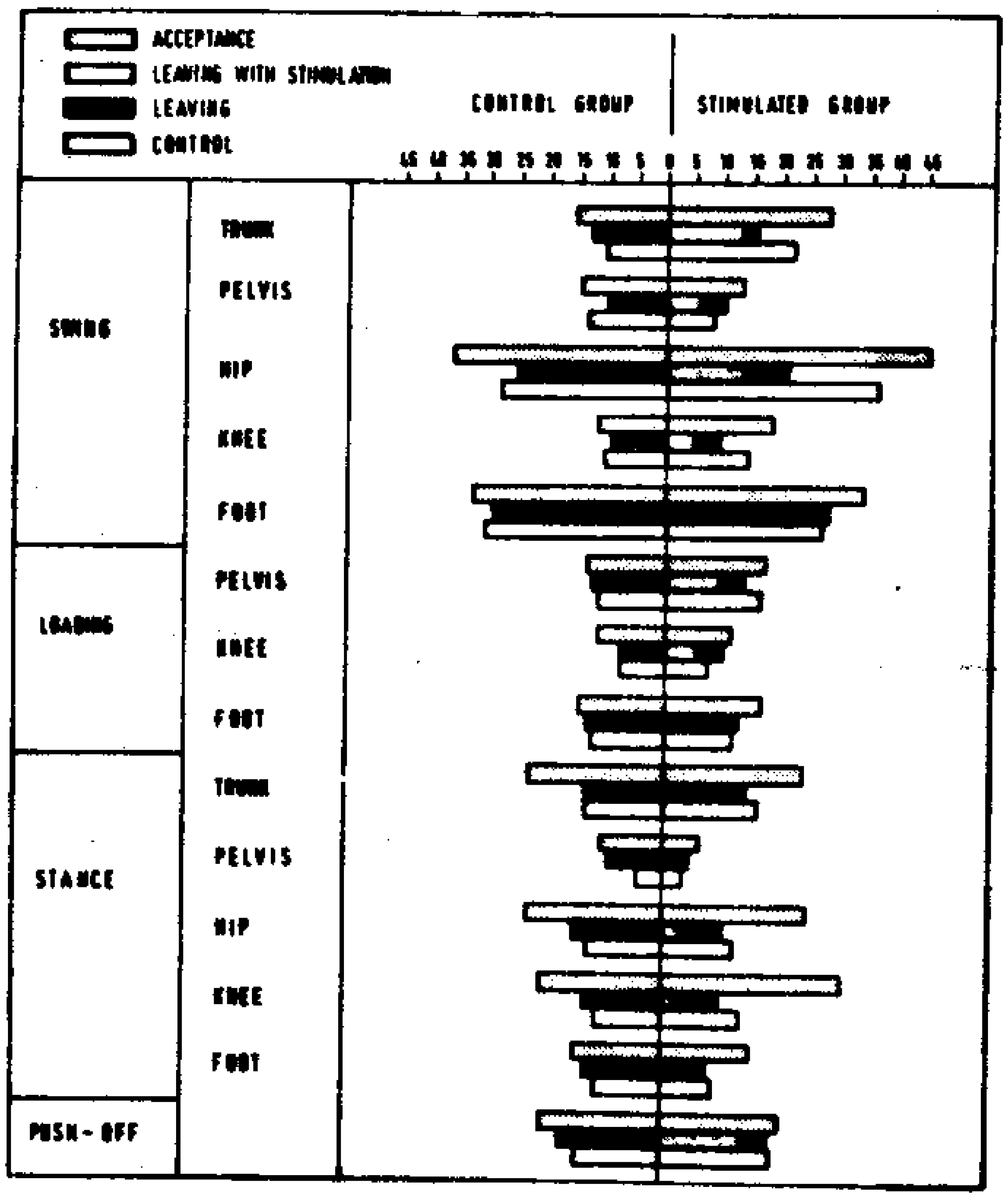

Fig. 7. Clinical kinesiological analysis of gait, scores of both groups.

accomplished at the begining, at the conclusion of therapy, and at the control after 5 to 11 months (Fig. 7). As an illustration, further improvement of the anom= alies with the multichannel stimu= lation at the end of therapy is also given.Together with tests of motor functions, the kinesiological analysis of gait reveals that ethical moment has been present at the selection of both groups. The stim= ulated group has included patients with age under 60 and extensive lesions attended by disturbances of sight, aphasy, contractures and sensoric lacks. At the begining of therapy, several patients could not move alone and their gait was initiated by the stimulation. The control group has consisted of patients with age over 60 and typ= ical capsular lesions. They were able to move by themselves before the therapy. Better kinesiological improvements have been achieved at the stimulated group, whose patients have been all able to walk independently before the conclusion of treatment. Observing motoric functions, further recovery has been observed in the stimulated group at the control exam= inations several months after the end of therapy. Lesser change has been obser= ved at the control group, where some applications of assistive devices have been required after the control period. However, the control observations can not be regarded only as the effects of therapy.

The improvements of the average step length, the average velocity of gait, and the average score of clinical kinesio= logical analysis of gait is given in Table 1 for both groups at the end of therapy and after the control post-therapeutic period. The values are normalised with the ini= tial ones at the begining of therapy and corre= spond with the results on Fig. 1 to 7.

	CONTROL GROUP		STIMULATED GROUP	
	END OF THERAPY	6-12 MONTHS AFTER	END OF THERAPY	6-12 MONTHS AFTER
STEP LENGTH	15%	18%	29% (34%*)	16%
GAIT SPEED	48%	68%	41% (58%*)	43%
KINESIOLOGICAL GAIT ANALYSIS	21%	27%	38% (74%*)	29%

Table 1.

For the stimulated group, the values in brackets with asterisks represent the immediate effects of multichannel stimulation. They can not be compared with the therapeutic effects and are given only as an illustration of possibilities of today not existent orthotic multichannel stimulation.

Diagrams of average ground reaction forces and of average distributions of centers of gravity under both feet during stance phases have been computed statistically as well as diagrams of average crutch loading measuring at least 40 steps (20). Results of a patient prom the stimulated group are given with their mean values (full line) and their standard deviations (dotted line) before the therapy (Fig. 8) and at its conclusion (Fig. 9). In the upper two force/time diagrams, higher (300 N) forces under the left foot of left hemiplegic patient, lesser (100 N) and shorter (5% of stride) crutch loading, shorter double support (5% of stride), better symetry between both legs, and existence of an active push-off mo= vement can be observed after the therapy. The time of average stride (100% on the time axes) has decreased from 1.92 seconds at the begining to 1.71 seconds at the end of therapy. Both lower x/y diagrams (Fig. 8 and 9) show the shift of central reaction forces under both feet to the left (5 mm), smaller dispersions (smaller windows of the standard deviations at 20, 40, 60, and 80% of stride), and the remaining lack of left heel landing in the initial stance which has not been improved by the therapy.

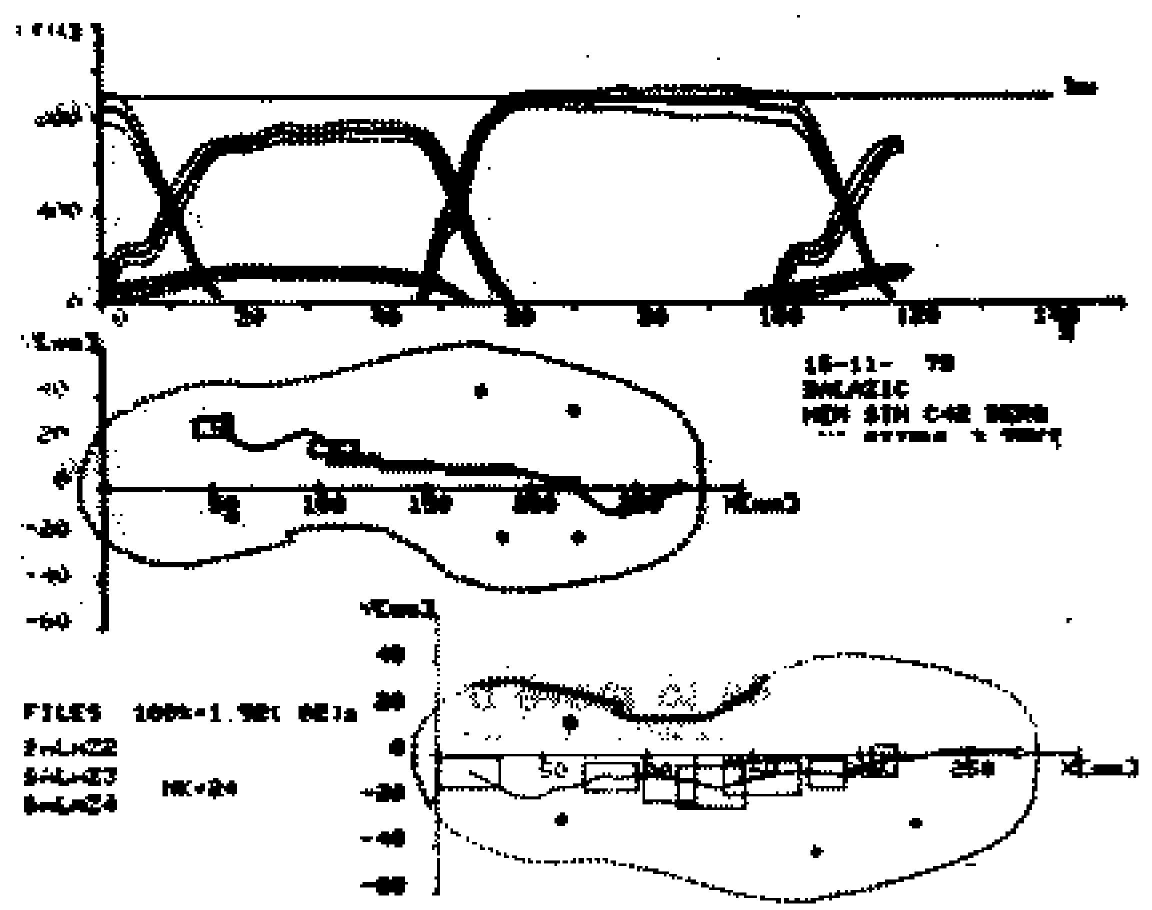

Fig. 8. Average ground reaction forces and their distributions, before the therapy.

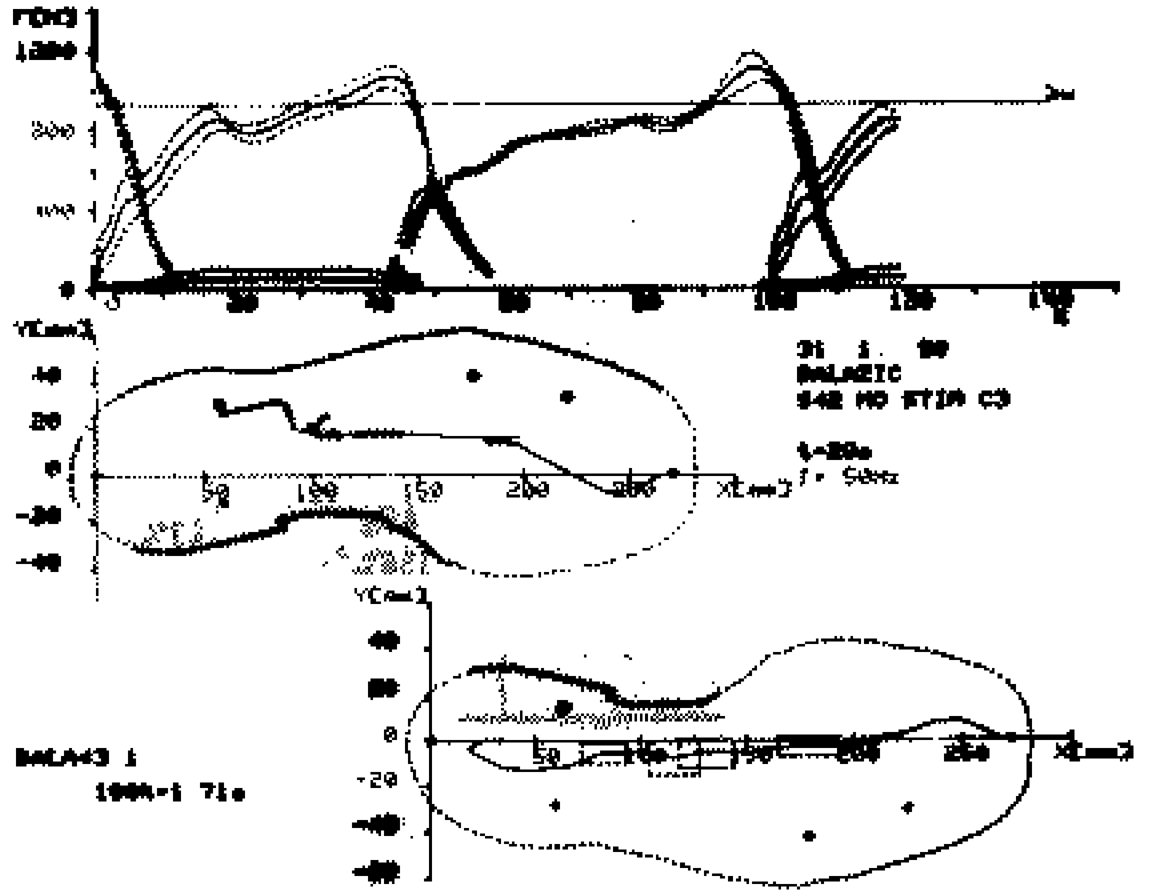

Fig. 9.
Average ground reaction forces and their distribu= tions, at the end of therapy.

Goniograms of average joint angles in the sagital plane have been computed statistically together with the average ground reaction forces during stance phases for a right side hemiplegic patient from the stimulated group (20). The mean values (full line) and the standard deviations (dotted line) are given for 46 steps at the begining (Fig. 10) and for 58 steps at the end of therapy (Fig. 11). From the goniograms of the right leg (right sides of Fig. 10 and 11), better hip flexion (8 grades) in the initial stance, better knee extension (10 grades) in the mid-stance, and existence of ankle dorsiflexion (9 grades) during the swing can be observed at the conclusion of therapy as well as higher ground reaction force (150 N) uder the right foot at the bottom two diagrams.

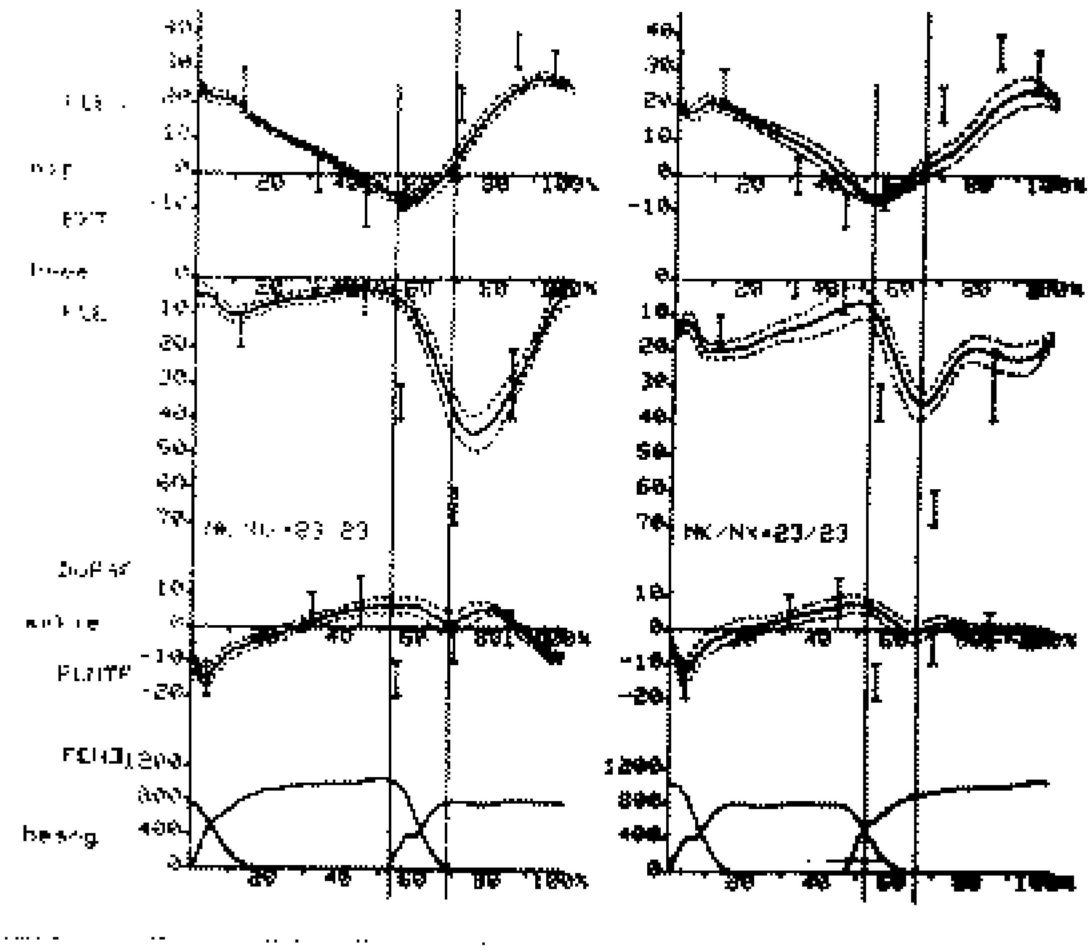

Fig. 10. Average goniograms and force basograms, before the therapy.

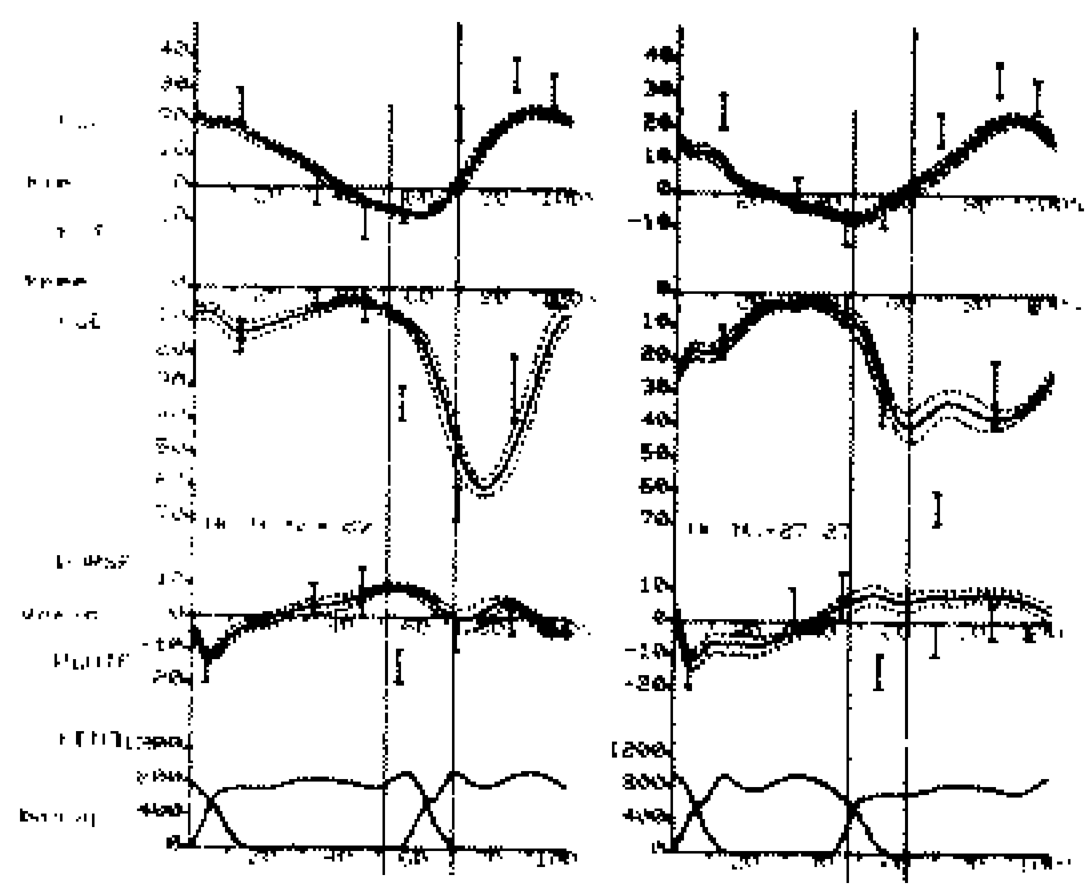

Fig. 11.
Average goniograms and force basoframs, at the conclusion of therapy.

CONCLUSION

Experiences with the immediate effects of multichannel electrical stimulation (2,7) have partly arised ethical obstacles at the selection of similar groups for this control study. The large extent of the therapy with accompanying tests and measurements for both groups together with the rather extensive time period (3 years) of the whole investigation have brought difficulties to accomplish the tests and measurements in equal conditions. Relatively small population of patients in both groups and considerable differences among individuals have not enabled statistically significant results about the therapeutic effects of multichannel electrical stimulation. Yet, they have been indicated and the investigation has given directions for further research and design on this field.

The presence of longer therapeutic effects implied in the secondary biomechanical parameters average step length and average velocity of gait is not quite explicit. Average forces, their distributions, average joint angles, symetry, etc. reveal more. Introduction of endurance measurements might add to the present results but is questionable from medical aspect. The psycho-physical and social statuses of patients, the impact of their living environment, their motivation and challenge for better improvement influence further the achieved recovery level and might reveal additionally the present results.

The multichannel electrical stimulation can reestablish the organisation of motor activity after extensive therapy. However, its therapeutic effects fade after longer periods with several patients. Localisation of its influences as well as their extent and duration remain still to be given on larger population of patients paying attention also to the neurophysiological part of the problem.

The investigation has shown too, that larger effects can be expected at the rehabilitation of proximal muscle groups. Thus, the application of already existent simple orthotic stimulators might solve the problems and has been indicated in several cases after the multichannel therapy. Future design of two- or more channel orthotic devices for home use should also esteem the correlations between antagonists.

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