

Biomechanical and physiological evaluation of FES-activated paraplegic patients*

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Abstract—Four paraplegic patients with traumatic upper motor neuron lesions at the spinal levels between D5 and D12 were activated by functional electrical stimulation (FES) and evaluated biomechanically and physiologically. After a training program aimed at strengthening the muscles of the lower legs, the patients were able to stand up, maintain the standing position, and walk for short distances while being supported. Biomechanical evaluation included weight bearing on the patients' own legs during standing as measured on a force platform and analysis of the time-distance parameters of the stride during walking as measured on a walkway. Physiological evaluation included heart rate and oxygen consumption at rest, when activated by FES in the sitting position, during standing, and during walking. The results obtained indicate that while significant standing and walking performances are achieved, the corresponding physical effort can reach relatively high levels requiring the support of anaerobic energy sources. The practical implications of these results are discussed.

INTRODUCTION

An important stage in the rehabilitation process of paraplegics is when these patients reach independence in a wheelchair, which is their principal means of self-ambulation. For standing or walking, usage of mechanical orthotic supports, such as long leg braces is very limited, especially after discharge of the patient from the rehabilitation center. This has been shown in a study (36) in which only 4 patients out of 28 spastic paraplegics used

mechanical supports for standing; of these only one patient actually walked. Our own experience shows that the main reason for not using the mechanical orthotic supports is the difficulty experienced by patients in attaching them to their spastic limbs, which sometimes requires help from another person. It should also be remembered that walking with these aids requires high energy expenditure from the patients (12). The development of substitutes for the existing mechanical aids is thus of great interest. In recent years, the functional activation of paralyzed muscles by electrical stimulation (FES) has gained the attention of numerous investigators.

Liberson (26) pioneered work concerned with functional electrotherapy to motor deficit rehabilitation in patients with a central nervous system lesion. In his study on stimulation of the peroneal nerve in hemiplegics he defined functional electrotherapy as a form of replacement therapy, required in cases where the impulses coming from the central nervous system are lacking. At the very time of stimulation the resulting muscle contraction has a functional purpose in locomotion, prehension, or in other muscle activity. Spastic paraplegics suffer from upper motor neuron lesions with normal spinal arc reflex. In these patients, the paralyzed muscles can be activated by electrical stimulation. At tetanic stimulation and with proper frequency and intensity, these muscles can be strengthened (17,31,34).

Kralj et al. (21) reported on an orthotic device using FES that enables the patient to stand supported by his own bones and muscle forces, substituting the less effective long-leg-brace calipers that require complicated daily mounting procedures. These authors have suggested

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that FES offers further advantages such as the prevention of muscle atrophy, the improvement of blood flow in the legs, prevention of muscle contractures, and the reduction in spasticity.

Investigation of the cumulative influence of electrical stimulation (ES) on muscle strength (22) has shown that in a patient with upper motor neuron lesion, atrophied muscles can be brought to a strength equal to that of normal stimulated muscles. In the two patients studied by Kralj et al. (22) a significant increase in muscle force and reduction in fatiguing was reported. It may be of interest to note the effect of ES on muscle strength in healthy young adults as studied by Romero et al. (35), who found an increased isometric strength of the quadriceps muscles after a treatment period of 5 weeks.

Electrical stimulation of the neuromuscular structures provides active forces for the patient to stand up, maintain the standing position and perform primitive walking. Standing up of a paraplegic patient by a two-channel electrical stimulator was analyzed by Bajd et al. (2) and compared with standing up of a healthy subject. Stimulation was on the quadriceps muscles, and motion was analyzed by stroboscopic photography.

Reciprocal gait of paraplegic patients with complete lesion of the spinal cord was generated by a four-channel stimulator (3). In the double stance phase of gait the knee extensor muscles of both knees were stimulated, and in the single phase the knee was kept extended only on the supporting side while swing of the contralateral lower extremity was achieved by cutaneously stimulating the afferent nerves and thus triggering the flexor reflex mechanisms (10,11,18,24). Gait analysis was done by means of joint goniometry (23) and, more recently by our group, by measuring the time-distance parameters of the stride (27).

The optimal location of electrodes for electrical stimulation was summarized by Benton et al. (5). While the vast majority of researchers make use of surface electrodes, there exists a tendency to introduce implanted electrodes which directly activate the muscle or nerve (7,30).

Coordinated self-activation of the muscles by means of the stimulator requires usage of hand switches, which demands constant mental effort from the patient in order to prevent accidents. A possible solution to this problem is by usage of EMG signals from healthy paraspinal muscles which activate the stimulator via a microprocessor (16).

The Biomechanics Laboratory of the Loewenstein Rehabilitation Hospital runs a research program in the ap-

plication of FES for the treatment and rehabilitation of spinal cord injured patients. The participating patients undergo a comprehensive training program of electrical stimulation of the paralyzed muscles of their legs. The objective is to improve their mobility by enabling them to stand for limited time and to walk for short distances supported by their own bones and muscles and with the help of walking-aids, such as Canadian crutches or a walker. This new means is not expected at this stage to replace the wheelchair but rather to allow easier mobility in cases, such as indoors, where the distances are short and the space is limited.

At the beginning of the training program the patient's muscles are strengthened, and at the end of it supported standing and walking are achieved. The whole training period is shorter than 6 months, and the regime of training is such that it allows routine everyday activity.

In this study our purpose was to evaluate biomechanically and physiologically the effects of FES on the patients studies, which included:

- 1) evaluation of standing and walking; and
- 2) evaluation of physical effort while being activated by FES in the sitting position, during standing, and during walking.

METHODS

Patients

Four paraplegics volunteered for the study; all had become paralyzed for traumatic reasons and were spastic due to upper motor neuron lesion. Their clinical characteristics are summarized in **Table 1**. These were the prerequisites for inclusion in the present study: 1) spastic paralysis of the lower limbs due to complete upper motor neuron lesion, 2) complete anesthesia of the lower limbs, 3) full range of motion in the joints of the lower limbs, 4) no pressure sores, and 5) general good state of health and high readiness for cooperation. None of the patients had undergone any sort of demolitive surgery in the paralyzed limbs. The patients—all nonneglected—were clinically examined and found free from cardiovascular, pulmonary, or renal problems. Additionally, the patients did not suffer from contractures (they had only a minor shortening of the Achilles tendon), urinary tract infections, or major psychological problems. Patients A, B, C and D took part in the biomechanical test, Patients A, B, and C participated also in the physical effort evaluation tests.

Table 1

Clinical characteristics of four paraplegic patients taking part in the study.

Patient	A*	B*	C*	D*†
Age	30	31	48	28
Years since injury	7	10	30	10
Cause of injury	work accident	shell fragment	car accident	gun shot
Level of orthopaedic injury	D8-D9 L1	D6-D7	C7-D5	D8-D9
Type of spasticity	Moderate	severe with a strong adduction	moderate	severe
Other lesions	comminuted open fractures in both tibia and fibula		closed fracture upper right femur	new bone formation at right hip joint, closed traction upper femur
Treatment of spinal injury lesion	fixation with A.O. plate	laminectomy D6-D7 and debridement		laminectomy D8-D9 debridement
Type of bladder Voiding	neurogenic spastic induced by trigger	neurogenic spastic induced by trigger	neurogenic spastic induced by pushing the abdomen	neurogenic spastic induced by trigger

*Participated in biomechanical evaluation tests.

†Only patient out of four who did not participate in physical effort evaluation test.

Apparatus for FES

The electrical stimulation was of tetanic form, given by a portable voltage-output stimulator. The power source was of eight 1.5 Volt rechargeable batteries. The stimuli were rectangular pulses of 0.3 m duration, intensity of 120 Volt, and frequency of 24 Hz. The resulting current was approximately 200 mA. These parameters are very close to those used in previous studies (5,21,22,24). Control of the serial stimuli in the muscle strengthening phase was manual at the beginning of the training and automatic afterwards, in a sequence of 3 stimulus followed by 3 s pause.

Surface electrodes were used, 2.5 cm square. The electrodes were of conductive rubber, reported to be most effective (22). Karaya gum self-adhering electrode pads were attached to the inner surface of the electrodes to improve conductivity. This material was found superior to conductivity gel or to wetting of the electrodes because it minimized skin irritation. The electrodes were further secured to the leg by micropore adhesive tapes.

Training Program

The training program was divided into three main stages: The first stage was dedicated to these steps:

a. The motor points of the quadriceps and gluteus muscles and the triggering points on the leg, which serve to provoke the flexion response, were searched. The exact

location of the electrodes was established in every patient at the motor points, where the response to the stimulus was maximal. No difficulty was encountered to reestablish the same location of the electrodes for every patient.

The quadriceps were stimulated, 5 cm above the patella and 8 cm distally to the inguinal area (**Figure 1**). In patients *C* and *D* the positive electrodes were split to allow attachment to the gluteus muscles. In patient *B* the split electrode was connected to the gluteus medius muscles. Patients *A* and *B* disliked stimulation of the gluteus maximus, as it also caused activation of the abdominal muscles, which interfered with their respiration. It should be noted that while stimulation of the gluteus muscles enhanced the extension forces necessary for standing, it sometimes also activated the unnecessary adducting muscles. The latter was partly avoided in patient *B* when the gluteus medius was stimulated.

The flexion reflex was activated by stimulation of the shank (24,38), by placing the electrodes on the anterolateral aspect of the leg, just below the head of the fibula. The result was simultaneous flexion of the hip and knee, together with dorsiflexion of the foot (**Figure 2**). It was especially important to avoid stimulation too near the head of the fibula, as this gave plantar instead of dorsiflexion of the foot because of the simultaneous activation of the tibialis posterior nerve. Placement of the proximal electrode was 4 cm below and 4 cm medial to the head of the fibula; placement of the distal electrode was 10 cm below and 3 cm medial to the head of the fibula. In patient *A*, the electrodes were placed lower and more to

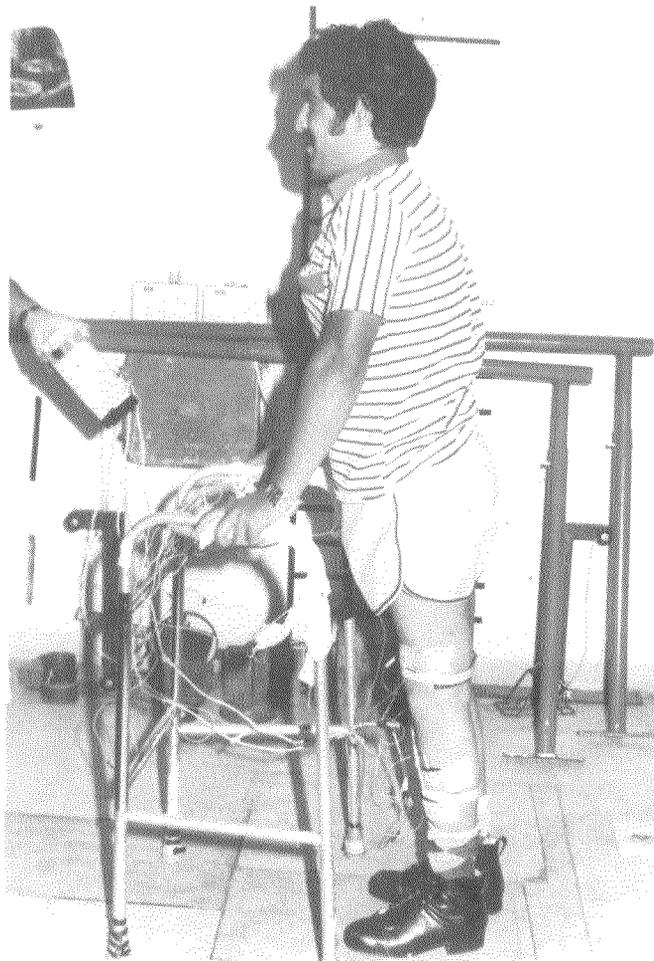
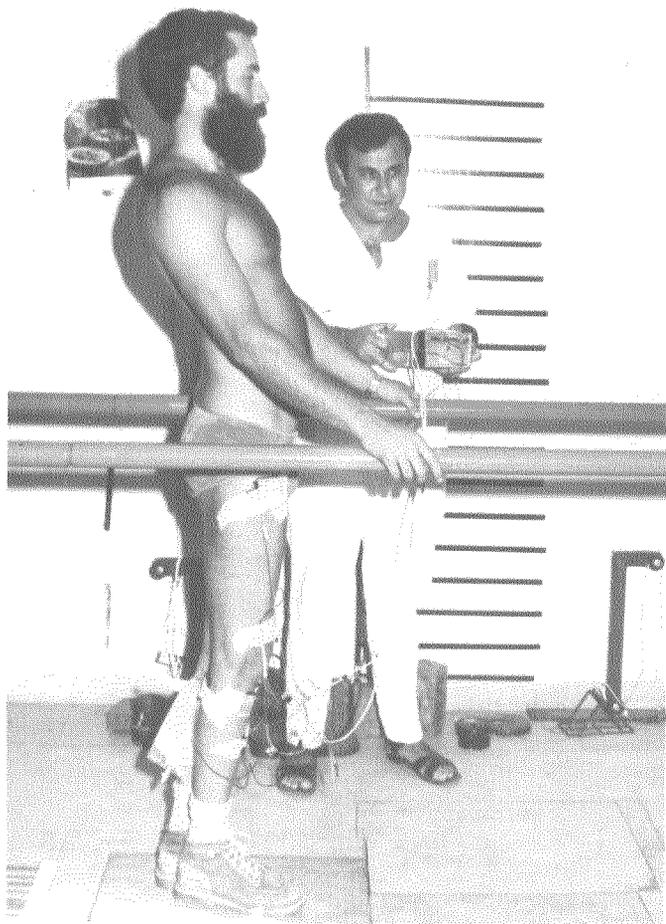


Figure 1
Patient standing by FES on forceplate for evaluation of weight-bearing on his legs, and demonstrating placement of the electrodes: *Left*: Patient *B* supported by parallel bars; *right*: patient *A* supported by walker.

the left, almost adjacent to each other, because of the peripheral soft tissue lesions he had on his shanks. The X rays of the area showed that location of the electrodes in this patient were above a metallic internal fixation plate in the tibia.

b. The patient's muscles were strengthened. Isotonic contractions of the quadriceps (17,23) and activation of the flexion reflex were achieved by using the FES when the patient was in the sitting position on the wheelchair. Training was performed with all the electrodes connected, except those of the gluteus muscles. The sequence of automated stimuli given during the strengthening procedure is (Figure 3) similar to the sequence used at a later stage to generate gait.

Stimulation of the quadriceps raised the lower leg against gravity up to full extension of the knee. Upon release of

the quadriceps, the flexion reflex was stimulated. After approximately 2 weeks of training 500 g sand bags were attached to the ankle to increase the resistance during the strengthening process. Adequate padding behind the legs was prepared to prevent their bumping against the wheelchair.

Stimulation of the gluteus maximus muscles was found necessary in patients with higher dorsal lesion, due to the very limited control of their pelvic girdle. Stimulating these muscles in the sitting position was technically difficult because hip extension resulted in slipping down from the wheelchair. Strengthening of the gluteus maximus muscles during the training period was therefore abandoned and was done in the standing phase instead. Specific description of the training procedure for each patient is discussed next:

Patient *A* began his training twice daily for 10 minutes, later reaching 30 minutes each time. Patient *B* had, in spite of his injury at the D6-7 level, partial sensation down to the inguinal region. For this reason, stimulation caused him discomfort in the first stages of training,



Figure 2
Patient *B* demonstrating flexion reflex during walking between parallel bars on the electric contact system and by which the time-distance parameters of the stride are monitored.

whenever the quadriceps electrodes were too close to this region. This problem was later avoided by removing the proximal electrodes further down to approximately the midhigh level, which was completely anaesthetic. Patient *C* was less spastic; therefore it was possible to activate both knees, separately for 15 minutes and after 5 minutes rest both were alternately stimulated. In patient *D*, 5 minutes of simultaneous extension of the knees were required before the activation of flexion and extension in order to reduce the high spasticity of this patient. It was thereafter possible to proceed with 15 minutes of alternate stimulation of the leg muscles, which was followed by 5 minutes of rest and another 15 minutes of training. Summary of training periods, muscle-activated and final walking aid used is given in **Table 2**.

In the second stage, the patients were trained to stand up and to maintain the standing position. This was achieved by applying continuous FES to the quadricep muscles and in some patients to the gluteus maximus as well. The upright time was adjusted to the ability of each patient and was limited, when bending of the knees was first noticed. As first supports, parallel bars were used. However, when the patient was able to maintain equilibrium with a walker or with Canadian crutches, these were used instead (**Figures 1 left, right**). The third stage was devoted to ambulation training while the patient was being supported on a walking aid, the type of which was determined to fit the patients' needs and abilities. **Table 3** shows the time, in which the patient first started walking, which was established when the patients were able to stand steadily between the parallel bars for at least 5 minutes. The last means of support needed in walking are described for each patient in **Table 2**.

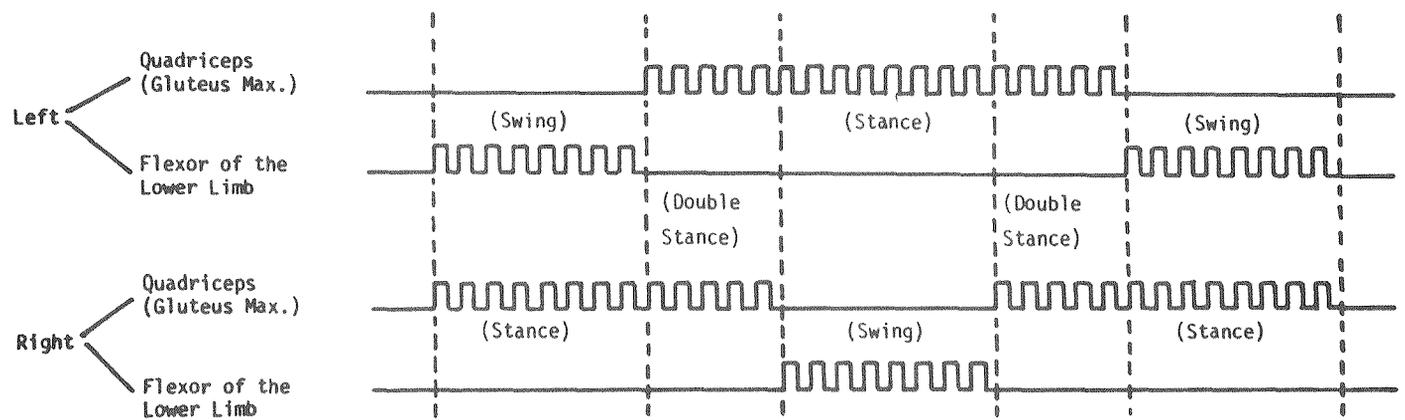


Figure 3
Schematic description of automated FES, applied in the sitting position and sequenced during walking.

Table 2

Summary of FES training program aimed at strengthening muscles of lower legs.

Patient	Training Period, days			
	A	B	C	D
Position				
sitting	10	14	27	21
standing	14	10	30	7
steps between parallels	14	150		30
Gluteus muscles		medius	maximus	maximus
Final walking aid (with FES)	walker	Canadian crutches		parallel bars

Table 3

Summary of standing times of the patients activated by FES.

Patient	A	B	C	D
Initial time, min	1.5	4.0	0.7	0.3
Ultimate time, min	20.0	15.0	2.2	20.0

TESTING PROCEDURE

Biomechanical evaluation

During standing, weight bearing on the foot was measured by Kistler force platforms on which the patient was requested to stand, while taking care to support his walking aids outside the platform area. The reaction force traces were time-integrated over the standard period of 1 minute, starting as soon as the patient stabilized after standing up. Stand-up and sit-down transients were not included in this measurement. With the results normalized by body weight, weight bearing on the feet and hands could be compared for a given patient at different periods of time and also for different patients. **Figures 1a, 1b** demonstrate a patient standing on the force plate while being supported.

Gait was analysed by a 5 m long electrical contact system described elsewhere (28,29) and in which time-distance parameters of the stride could be evaluated (**Figure 2**). This method is suitable for monitoring of supported gait, such as exhibited by the patients tested in this study. These parameters were determined: contact time, swing time, stride time, stride length, velocity, and step symmetry. These parameters were calculated for each foot separately, but simultaneously, by an IBM micro-computer. Supporting aids used by patients during ambulation are described in **Table 2**. The biomechanical

evaluation described above was done once every 2 weeks for each patient.

Evaluation of physical effort

While the patient sat inactive in a wheelchair, rest data of heart rate and oxygen consumption were taken (1,8,9,13,19,25,33,41). Thereafter FES was applied in the sitting position for a 30-minute period. During the next 2 minutes, heart rate and oxygen consumption measurements were performed. After a 15-minute rest, the patient stood for at least 15 minutes, after which heart rate and oxygen consumption were measured again. At the end of another 15 minutes period of rest, patients A and B walked for at least 5 minutes. Heart rate and oxygen consumption were measured during the last 2 minutes of walking. Heart rate was monitored by a Mobile Cardio/Sentinel with Telemetry (M.G. Moder 656/F). Oxygen consumption was evaluated from expired air collected in a Douglas Bag (20,40). A wet Gasometer (Meterfabriek Dordrecht Type C) was used to measure the volume of expired air. Infrared carbon dioxide analyzer Capnograph Godart and Oxymeter Godart Rapox were used for measuring carbon dioxide and oxygen concentrations. Oxygen consumption was calculated according to a formula suggested by Saksena (37). Evaluation of physical effort was done after a training period of 6 months, three times for each patient with 1-week intervals between the tests.

RESULTS

Biomechanical Results

The detailed biomechanical results were reported separately (27). Altogether, weight bearing on the feet during

standing showed a great variability for all patients tested. However, while the early traces of weight bearing were characterized by numerous fluctuations and spikes, the curves tended to smoothen and stabilize over the span of time of FES training. The traces obtained from standing when supported by parallels appeared somewhat smoother, with reduced fluctuations and spikes, compared with those obtained when supported by a walker. No attempt was made to quantify this observation. Summary of the averaged standing results and their extreme values for all four patients is presented in **Table 4**. Results are expressed in terms of percentage of body weight borne by the feet of the patients. These averages were obtained, as previously described, by time integration of the traces over a measuring period of 60 s and normalizing the results obtained for body weight and time.

Table 4
Weight-bearing on the feet while standing during FES.

Patient	Average of daily results	Extremes
A	65.3 ± 6.5	59.1–74.7
B	60.2 ± 13.7	42.1–82.2
C	40.6 ± 8.2	33.6–53.6
D	71.2 ± 6.5	66.2–80.3

Results are expressed as percentage of body weight ± standard deviation.

A typical walking test output is demonstrated in **Table 5**. Variability of the measured time-distance parameters of the stride during a single walking test is expressed by the standard deviation (SD) of the mean of the results. This reflects the consistency of walking of the patient and of his repetitive movements on the walkway. The differences existing between tests performed on the same day were not significant compared with those obtained on the same patient in different days. We have earlier

shown (27) that in order to express the patient's walking state on a testing day, the average of the walking tests of that day is the most adequate information.

These main features in the walking results were present with the other patients as well, except for the following differences. In patients *B* and *D* improvements in the time, and in the distance parameters were of comparable values. Patient *C* initially proved able to walk between parallel bars. However, due to his advanced age, electrical stimulation on him was restricted to standing only.

In plotting the time variations during the followup period of the walking parameters a logarithmic curve fit was made. This was selected since it gave the highest correlation coefficient compared with linear or exponential regression (27). Time variations of the daily average of the nondimensionalized walking parameters of patient *A* during the followup period are shown in **Figure 4**. The corresponding nondimensionalized coefficients of the logarithmic curve fit are shown in **Table 6**.

An interesting observation from **Table 6** is the higher correlation coefficients of the time parameters (stance and stride times) compared with the distance parameters of walking (e.g., stride distance). Furthermore, the coefficient *b*, expressing the rate of variation shows greater improvement in time compared with distance parameters during the followup period. Walking velocity, however, had high values of both correlation and slope coefficients. The highest variability was found in two other time parameters: swing time and double stance time. It should be mentioned in this respect that FES was commanded by the patient himself through two hand switches attached to his walking aid. Timing of the reciprocal gait was therefore established at the patient's will and at his own convenience. These findings of the differences clearly indicate that the parameters related to contact of the feet with the ground were being more steadily controlled compared with the other parameters.

Table 5
Representative walking test including time-distance parameters of the stride along the walkway.

	Contact Time, s	Double Contact Time, s	Swing Time, s	Stride Time, s	Stride Distance, cm	Velocity, cm/s	Time Symmetry, dimensionless
1	3.75	0.75	1.75	5.50	51.35	9.34	0.50
2	2.75	0.25	2.75	5.50	51.35	9.34	0.45
3	4.50	2.00	1.50	6.00	62.16	10.36	0.42
Average	3.67	1.00	2.00	5.67	54.95	9.68	0.46
Standard	0.72	0.74	0.54	0.24	5.10	0.48	0.03

Values presented were taken from the right foot output, which was very comparable to that of the left foot.

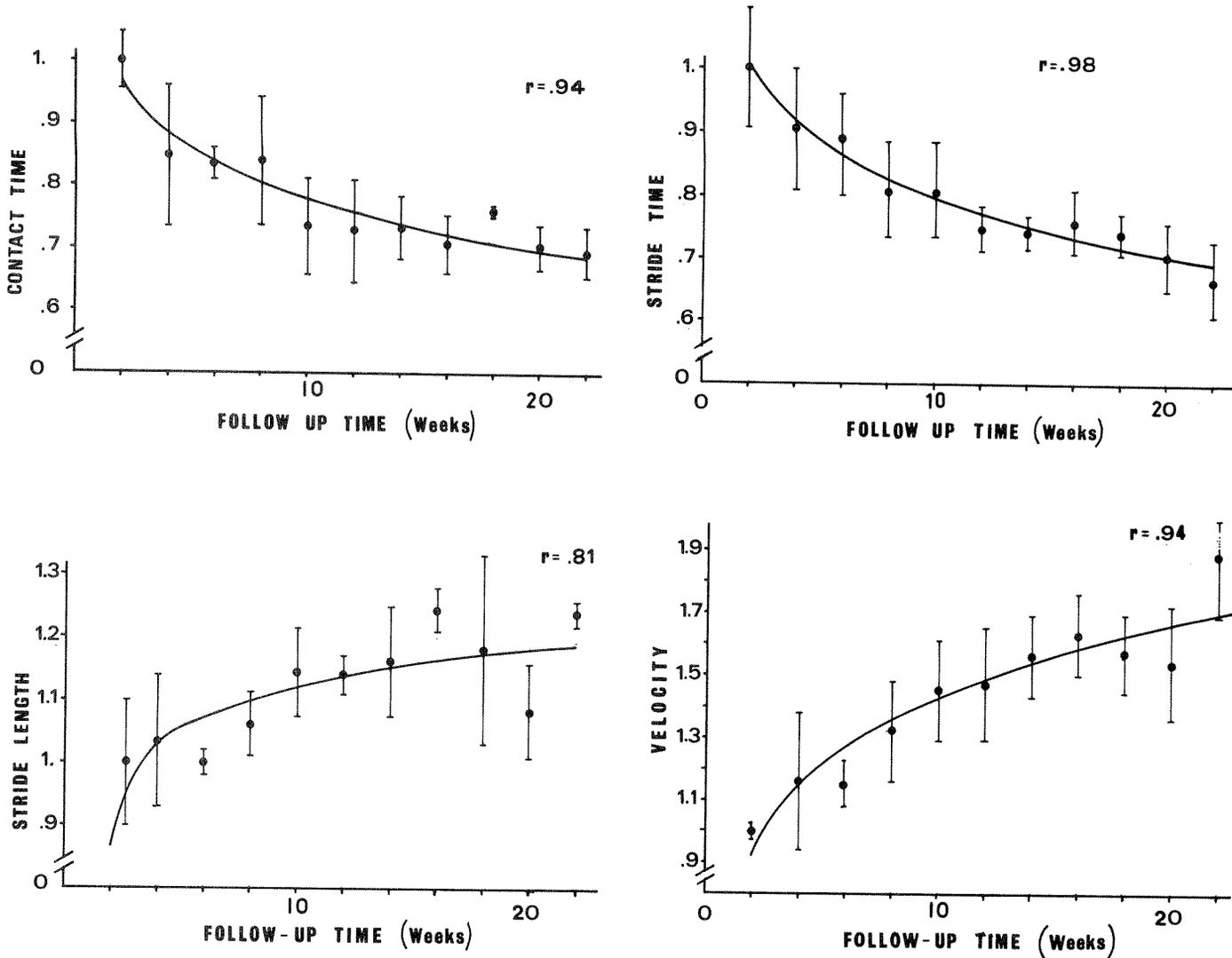


Figure 4
 Typical time variation of stride parameters during the followup period. Nondimensional values are referred to value at initial time, denoted arbitrarily as 1.0. Actual initial values are as

follows: Contact time 5.30 s, stride time 7.50 s, stride length 39.2 cm, velocity 4.50 cm/s⁻¹.

Physical Effort Results

Values of heart rate and oxygen consumption at rest and during FES in sitting, standing, and walking are summarized in **Table 7**. The percentage increase of heart rate and oxygen uptake during FES is referred to the resting position.

As can be seen, in the sitting position, FES caused in all patients an increase in the heart rate by over 20 percent. The oxygen uptake increase in these conditions was of the order of 100 percent. Standing required an almost 50 percent increase in heart rate in patients *A* and *B*, and over 100 percent in patient *C*. Oxygen uptake, on the

other hand, was tripled in all the patients. Walking, as performed by patient *A* and *B* requested a further increase of more than 150 percent in heart rate. Oxygen uptake was during walking about 5 times higher. The significance and interpretations of the results are examined next.

DISCUSSION

Progress in science and technology during the last two decades led to the development of new devices and treatment methods, giving new hopes and opening possibilities to better rehabilitation of paralyzed patients (15).

FES as a therapeutic technique for physical treatment and rehabilitation is constantly expanding (14,39).

Standing upright is important to the well-being of paraplegic patients and is believed to improve the physiological processes in the body, i.e., blood pressure, blood circulation to the lower limbs and functioning of the gastrointestinal and urinary tract systems. Weight bearing on the legs also has a positive effect on the long bones of the lower limbs and controls osteoporosis to a great extent. In a recent study (4) it was shown that FES also reduces spasticity. This effect has also been confirmed by our group when antispastic drugs were reduced as a result of FES application (6). At the present, FES serves mainly as an orthotic aid during ambulation and as a treatment method for muscle strengthening. However, the effort invested during FES application has not as yet been evaluated; this includes oxygen uptake and cardiopulmonary and metabolic response.

The objective for the mechanical part of this study was to provide means for quantitative evaluation of the adaptation and training procedures at its different stages. Parameters directly related to the desired ultimate goal of FES, standing and walking, were selected. In standing,

the parameter investigated in the followup process was the weight borne on the patients' own feet and the residual weight borne by the hands. Weight bearing on the patients' own feet in a prolonged period of time was shown to be smaller than the almost full weight bearing which can be achieved for smaller periods of time (Table 4). This fact is attributed to the different posture requirements imposed for an erect standing position with very little support compared with supported standing and reciprocal walking. In the first case, stabilization of the pelvic girdle in a vertical posture demands intensive stimulation of the hip extensors and the hip abductors, which caused considerable inconvenience to some of the patients, especially those with the higher level spinal lesion.

In walking, time-distance parameters of the stride were selected as especially suitable for a supported gait regime, and introducing minimal interference with the undisturbed gait pattern of the patient. Most of the mechanical parameters improved during the training and followup period, except symmetry parameters which had reasonable values from the beginning of the followup and remained so throughout followup.

Standing by means of FES is due to a functional contraction of the lower limbs antigravitatory muscle and invested work of the upper extremity muscles. In this case, unlike in passive standing with long braces where the patient can be completely supported on the orthotic device, the stimulated muscle is being contracted against body weight. During gait usage of the upper limbs as well as the upper trunk is much more extensive, especially in the single stance and swing phases of the walking cycle.

To evaluate the reaction to effort related to the activation of the lower limb muscles by FES, three activities were studied: full extension of the lower leg in the sitting

Table 6

Nondimensionalized coefficients of logarithmic curve fit $y = a + b \ln x$, r = correlation coefficient of fit, for walking parameters for patient A.

Parameter	<i>a</i>	<i>b</i>	<i>r</i> ²
Stride time	1.00	-0.13	0.96
Stance time	0.97	-0.12	0.89
Stride length	0.97	0.09	0.65
Velocity	0.92	0.32	0.88

In all parameters initial value = 1.0.

Table 7

Results of physical efforts evaluation during FES in the sitting, standing, and walking positions.

Test	Subject	Rest	Sitting		Standing		Walking	
		mean	mean	incr. %*	mean	incr. %*	mean	incr. %*
HR, bpm	A	62	77	24	92	48	155	150
	B	63	78	24	88	40	165	162
	C	67	82	22	136	103		
\dot{V}_{O_2} , ml/min ⁻¹	A	164	330	101	469	186	812	395
	B	251	479	91	702	180	1381	450
	C	204	391	92	628	208		

*Percentage increase is related to the resting position.

HR = heart rate in beats per minute.

\dot{V}_{O_2} = oxygen uptake.

position in a wheelchair, standing between parallel bars, and walking supported with parallel bars or walkers.

During sitting, 20-minute stimulations of the quadriceps raised the oxygen uptake to 330, 479, and 391 ml/min⁻¹ for patients A, B and C, respectively. The increase in heart rate was approximately by 15 beats per minute (bpm) for all three patients. For comparison a similar test in the sitting position was performed on an able-bodied healthy male subject, aged 42 years, who was requested to continuously extend and flex his knees for a period of 20 minutes. The resulting oxygen uptake was 726 ml/min⁻¹ and heart rate increase was by 37 percent (80 to 110 bpm). This difference indicates that unlike in paraplegics who are activated by FES, in healthy subjects selective contraction of the quadriceps muscles alone is not possible. Synergic muscles such as abdominal muscles participate as well in knee extension in the sitting position, resulting in a bigger increase in oxygen uptake and heart rate.

During standing and walking of paraplegics activated by FES, it should be reminded that in our patients there was a significant amount of support on the hands. This makes difficult comparison with able-bodied subjects, in whom the lower limbs are almost solely involved. During standing, for instance, heart rate values increased for patients A, B, and C to 92, 88, and 136 bpm and the oxygen uptake to 469, 702 and 628 ml/min⁻¹, respectively. The reported oxygen consumption of normal subjects during standing (1) is 360 ml/min⁻¹, which is significantly lower than the values obtained for paraplegics.

The reported differences (1) between the work done by the upper limbs and that of the lower limbs have been attributed, among other things to the differences existing between their volumes and histological structures. The lower limb muscles, specifically the quadriceps consist mainly of red, oxidative slow-twitch fibers. On the other hand, the upper limb muscles consist of white, glycolytic fast-twitch fibers. These differences find expression in ergometric tests aimed at evaluating maximal oxygen uptake. Tests done recently on paraplegics with D5-D10 level of injury (9) have shown that the maximal oxygen uptake in these patients is 1520 ml/min⁻¹. For able-bodied subjects using their lower extremities, this parameter was reported (1) to be of the order of 3,500 ml/min⁻¹.

Free walking in normal subjects requires an oxygen uptake of approximately 900 ml/min⁻¹ (41). During walking the heart rate values increased for patients A and B to 155 and 165 bpm and the oxygen uptake to 812 and 1,381 ml/min⁻¹, respectively. By comparing the submaximal effort levels, i.e., the percentage of the actual

oxygen uptake to maximal oxygen uptake it is possible to evaluate the results obtained during walking. While in normal subjects this is found to be approximately 25 percent, the corresponding values for paraplegics activated by FES and 53 percent and 90 percent for patients A and B, respectively.

It has been reported (1) that efforts exceeding 50 percent of those corresponding to the maximal oxygen uptake result in a sharp increase in lactic acid levels in the blood. It should be pointed out that lactic acid levels were tested in patients A and B during walking and were found of values 68.3 and 51.1 milligram percent, respectively. These results reconfirm the high level of the invested effort of our patients during walking and clearly demonstrate that aerobic energy source was not sufficient and such an effort must be supported by anaerobic energy sources as well.

In conclusion we found that activation by FES in the sitting position as a daily home application for spastic paraplegics will exercise and strengthen the muscles. Our physiological data complement, mostly positively, the previously reported effects of FES. The use of FES as an orthotic aid for standing could be a valuable tool, especially in young patients. Unlike metal braces, FES can be more easily and simply mounted and applied and, above all, standing is carried out by functional active contraction of muscle groups.

Standing therefore, can be performed by the paraplegics and should be exercised at home daily for its benefit in minimizing orthostatic effect on blood pressure, strengthening of the antigravitatory muscles, and improvement of general physical capacity. Efforts invested in gait generated by FES seem to reach very high submaximal levels, as indicated earlier. Such an exhaustive effort can be carried out only for a few minutes by young patients. Optimization procedures aimed at reducing the energy costs of FES, especially during walking should therefore be studied and implemented in order to safely allow FES application by paralyzed subjects.

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