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CHAPTER 34

FES gait restoration and balance control in spinal cord-injured patients

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The status of gait restoration in spinal cord-injured patients by means of FES is reviewed and the main aspects are discussed. This introduction highlights the issues of balance control, stimulation sequence synthesis, and control of enhanced gait modes containing unbalancing. The use of statically unstable dynamic weight-transfer phases is important for enhanced gait modes. To show how this phase can be employed the mode of static balance currently used for FES-assisted four-point gait in paraplegic patients is discussed, and how this mode of gait can be converted to a semi-dynamic gait mode is described. The possibilities and consequences of such an approach are briefly discussed.

Key words: Functional electrical stimulation; Paraplegia; Balance control; Gait

Introduction

Since 1979, important advances have been made in locomotion restoration of spinal cord-injured (SCI) patients by means of functional electrical stimulation (FES). The methodology developed for FES-enabled standing-up, standing and sitting has demonstrated that reciprocal bipedal gait restoration in these patients was feasible (Kralj and Grobelnik, 1973; Kralj et al., 1979, 1980; Brindley et al., 1979; Marsolais and Kobetic, 1983; Petrofsky et al., 1983; Holle et al., 1984). Consequently, FES control combined with passive orthotic devices was developed and promising results emerged (Andrews, 1986; Popović et al., 1989; Hirokawa et al., 1990). Here, we briefly describe the state of the art of FES which has enabled locomotion function restoration in SCI patients, and draw attention on balance control, stimulation sequences synthesis and control of enhanced gait modes containing a dynamic weight-transfer phase. The analysis of FES-enabled gait indicates that patients predominantly rely on static stability, hand-controlled balance and generation of propulsion forces. Such a gait is energy-consuming, inefficient, slow and functionally very limited. To enhance functionality and increase speed, FES-stimulated muscles providing propulsion forces must be included in the gait cycle. This would yield efficient energy exchange among the body segments from potential to kinetic energy and vice versa. The latter can be accomplished only if dynamic transfer phases are inserted into the gait cycle. It is important to note that faster link velocities and a more vigorous gait may increase the stress and loading on body segments and joints, provoking, if rectifying measures are not taken, the development of secondary pathologies and possibly long-term destruction of joints (Kralj et al., 1989, 1990a).

FES goals and accomplishments

A commonly accepted long-range goal of a FES system for locomotion restoration in SCI patients is to convert the wheel-chair bound to walkers who will

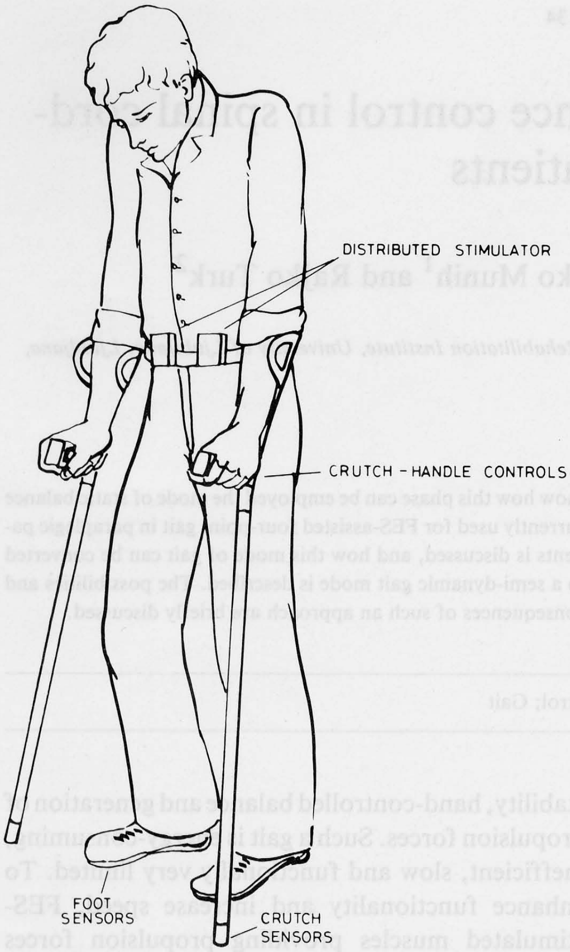


Fig. 1. FES system as proposed for reciprocal gait restoration in SCI patients. It is a distributed modular set-up including external sensors, crutch handle controls and sensory feedback.

occasionally still use the wheel-chair. The FES walking should be capable of negotiating rough terrain, including stairs, and permit work, sports- and entertainment-related activities. For the time being, there are no expectations for achieving active balance in these patients. Therefore, they are dependent on crutches or other balancing and partly supporting aids. Nevertheless, balance aspects are important. Balancing capabilities are not only related to dynamic but also to semi-dynamic gait. Balance control is crucial during standing-up and other transitions (Kralj et al., 1990). Semi-dynamic gait includes a brief tipping unstable-phase.

No matter which stimulation technology is used the current state of sensor development and associated control problems is inadequate for the immediate realization of total body implanted systems. For cosmetic reasons, a distributed modular FES system, such as that depicted in Fig. 1, is most likely to be developed and marketed once the problems of energy consumption and balance mentioned above are solved. For practical reasons chronic users will select implanted systems with an external control unit, while for patients selection, training and functionality testing, surface electrodes systems will be frequently applied. To date, more than hundred SCI patients have been supplied with different FES systems in Ljubljana (Kralj and Bajd, 1989). The types of system used for each injury level are summarized in Fig. 2. Here, two-channel stimulation is provided for standing only, four-channel stimulation for walker or crutch-assisted four-point walking, and six-channel stimulation mostly for research tests and demonstration purposes. About 10% of all admitted SCI patients are candidates for advanced FES rehabilitation (Jaeger et al., 1990). Only 50% of them are utilizing walkers and only 10% crutches. Many of them are using FES systems at their homes. Fig. 3 displays the wheel-chair-attached folding frame for standing and Fig. 4 illustrates patients using FES gait and

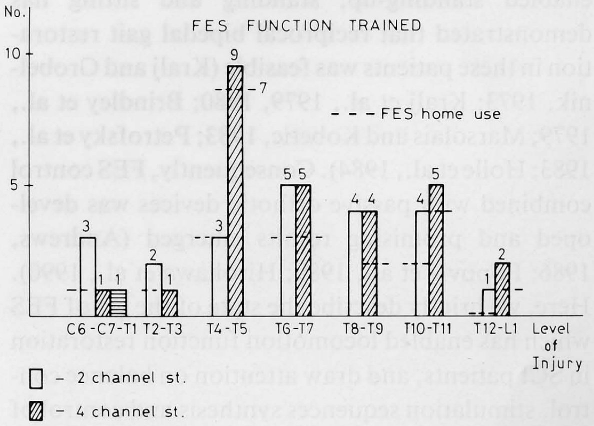
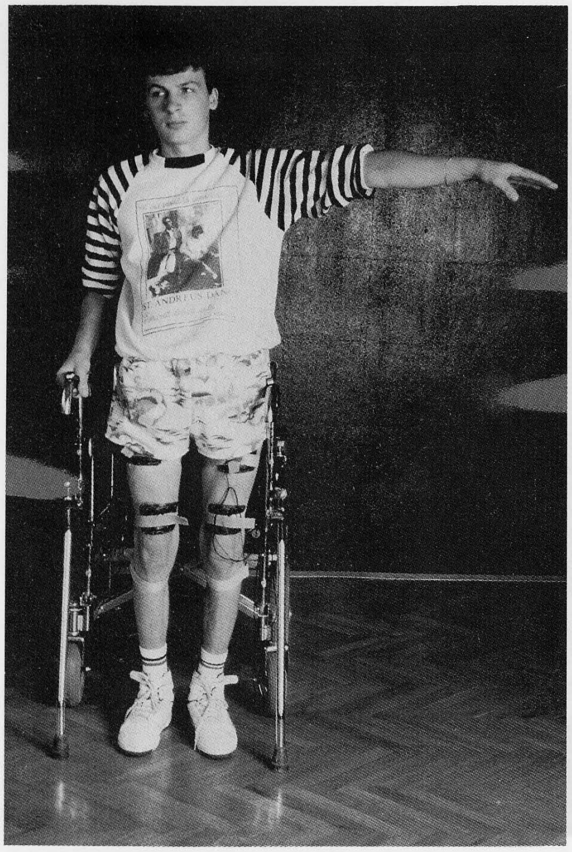


Fig. 2. Patients are grouped according to the type of FES stimulation employed and according to the level of spinal cord lesion.

a



b

Fig. 3. Wheel-chair attached folding frame for standing. The frame is not interfering with regular wheel-chair functions, but does allow patients to stand-up and select locations for performing some functional tasks (*b*). In (*a*) the patient is demonstrating stability and the ability to use one hand for simpler manipulative tasks with smaller objects. This testing is performed for each hand and is included in regular FES training.

crutches for balance. With FES the time of standing is limited because of fatigue. Typical standing times range from several minutes up to an hour (Kralj and Bajd, 1989). Switching to a new posture, using intermittent FES activation of different muscles, substantially prolongs the standing time (Kralj et al., 1986). The characteristics of our simple FES gait are far from normal gait. In particular, the progression velocity is small, in the range of 0.1 – 0.4 m/sec. Only in rare cases can velocities of 0.8 m/sec or higher be achieved (Marsolais and Kobetic, 1987). Because of energy inefficiency and static characteristics of gait the walking distance generally is limited to around 20 m. Several hundred meters can be achieved in some cases. Hybrid systems which rely on mechanical knee locking during standing and restricted ankle joint in plantar flexion submit easier balance. Patients can thus remain standing for nearly unlimited times (Andrews et al., 1989). The gait performance of patients using hybrid systems is improved in several ways compared to simple FES-enabled locomotion. The mechanical support spares FES muscle power and the energy expenditure is reduced. It is our contention that improved FES control could achieve the same improvements. Thus a hybrid system would only be indicated in cases where mechanical bracing is needed because of a partial peripheral lesion. In the present work, we a

b

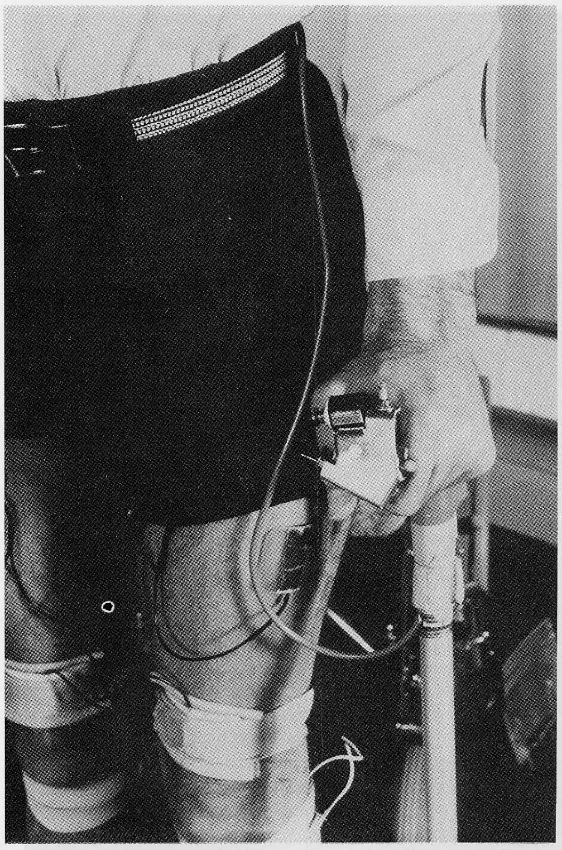


Fig. 4. Patient equipped for four-point walking using FES with crutches for balance assistance (*a*). In this case only a single switch as swing phase trigger is utilized. In (*b*) a more advanced but experimental crutch handle set of controls is displayed.

have focused our attention on these aspects related to the FES gait enhancement and on improved understanding of balancing control during FES-enabled gait.

The measurements of FES-enabled gait in SCI patients show very high energy consumption (Marsolais and Edwards, 1986), and consequently considerable inefficiency. This results in a very low endurance. The inefficiency of the gait is also a consequence of low progression speed. Typical results for our patients utilizing four channels of electrical stimulation are similar to the results obtained by other research groups. Four channels of FES are used as follows: two channels are used to stimulate the left and right quadriceps muscles, thereby providing knee locking during stance and double stance phases. The two remaining channels are utilized to evoke left and right side flexion withdrawal reflexes. The reflex-provoked movement is used for providing a swinging movement. The incorporation of reflex-triggered lower limb flexion into the FES-assisted gait cycle results in very simple hardware, reasonable patient control autonomy, and the lowest possible number of FES stimulation sites. This is the simplest possible FES-enabled gait in completely lesioned SCI patients. This approach is important as it proves that the preserved neural mechanisms of the pathologically organized and dissected spinal cord can be incorporated into the FES gait restoration scheme. Using surface electrodes to simply trigger the reflex has some disadvantages because the electrodes have to be accurately positioned. In addition, habituation of the reflex causes variations in the flexing movements and is dependent on stimulation amplitude, elapsed time and stimulation timing. Our last ten years of FES developments for SCI patients were predominantly concerned with proving feasibility. Recently, the field has entered a stage of development for a chronically usable and marketable system, because FES is recognized as being a potential and promising rehabilitation modality. In spite of the disadvantages, simple gait is possible and numerous patients are using it daily (Kralj and Bajd, 1989). We are seeking to enhance four-channel FES gait using approaches described below.

Enhancement of FES enabled gait

With the four-channel FES system only bilateral m. quadriceps stimulation is used to provide knee

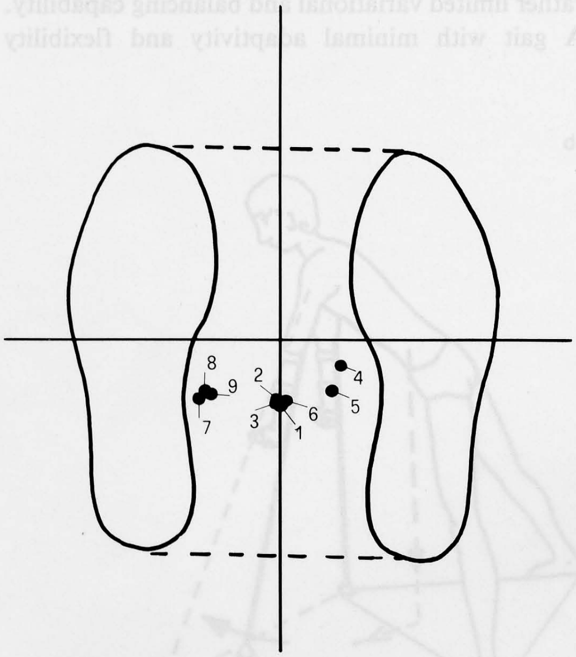


Fig. 5. Bilateral balanced erect standing with FES shown without balancing and support mean forces. Such standing has a support area which is similar to that of normals. During FES standing the patients make exclusive use of the safest central part of the support area.

joint stability during gait. The hip joint is stabilized by gravitational forces and through the opposing ligamentous locking of the hip joint. The ankle joint is stabilized by horizontal forces applied to the crutches by the hands. To preventing tipping, the patient adjusts the body position using the support forces at its hands. This posture can be simplified by considering the body as an inverted pendulum freely movable only at the ankle joint, neglecting trunk hyperextension movements. In Fig. 5, the supporting area is depicted for quiet standing with the actual locations of the ground force reaction vector (GRV). For quiet standing points 1 – 3 and 6 apply, and when FES of hip extensors/abductors occurred, the GRV was moved to points 4, 5, 7, 8 and 9. Similar relocations of the GRV can be accomplished by the patient himself if he exerts appropriate forces with his hands. If during such standing intermittent bilateral stimulation of the gastrocnemius and soleus muscles is added, the patient can stand up on his toes with a little learning, but he must assist the balance with his hands. Repeating this procedure makes the patient aware of when he should lean forward when standing on his toes. This experiment indicates that the patients is capable, when taught before a mirror, of using his hands to displace his GRV near to the edge of the heels or in front of the toes. SCI patients who sustained a complete lesion at the level of T-10 and upwards to T-4, all learn to adjust their balance during FES gait using either trunk movement or the hands to adjust forces exerted on supporting devices such as walkers or crutches. Their walking starts from a static balanced standing as depicted in Fig. 6, and the static stability is maintained throughout the walking cycle. This kind of static balance is characterized by GRV never leaving the support area during forward progression. The supporting area is rather large in the case of walking with crutches (Fig. 6*a*). During each single phase of walking the patient moves his ground support leg or crutch forward; however, the GRV is moved forward mostly during the four-point stance. After this is achieved, the patient moves the GRV forward in the new area of support by using the hands to push the body weight forward and to prepare the opposite leg for a step. Sometimes patients have difficulty to move a crutch or a leg. The reason is because they have not unloaded it properly.

Note that during the four-point stance the hands are used to push and move the body forward and thereby displace the GRV to its new location. Therefore we conclude that in such a gait propulsion is generated by the hands and remaining trunk muscle forces during the four-point support. Propulsion can also be generated during three-point contact when both crutches and only one leg are supporting the body. Already here we see that a propulsion force, generated, for instance, by plantar flexors stimulation, may substantially reduce the forces required by the hands and improve forward propulsion. A sequence of supporting area polygons formed by the legs and crutches during four-point gait is depicted in Fig. 7. The figure clearly illustrates the static balancing of the gait. The literature on quadrupedal locomotion (McGhee and Frank, 1968; McGhee and Kukner, 1969) indicates that theoretically 5040 modes of quadruped gait are possible, but only three ensure static stability at all times. Among these three gaits, only one is optimal as it maximizes the degree of static stability. This gait was named crawl gait. Fig. 7 is instructive as it demonstrates that SCI patients employ a crawl gait while walking. They are so afraid of falling that they select the most stable gait. The figure also indicates that – if provisions could be made to improve stability of hip joint, and a regime of different gait training utilizing an improved semi-dynamic stability was given – walking speed and energy consumption could be substantially enhanced. There is, in fact, a vast arsenal of possible gait modes to select from considering a four-point gait. Measurements of the GRV displacement with time using especially equipped force shoes (Kljajić and Krajnik, 1987) confirmed this statement. In patients, the GRV movement range is small and shows total unloading of the leg, well before the GRV reaches a boundary of the area of support (see Figs. 7 and 8). Confirmation of this finding is evident from the narrow vertical force standard deviation in Fig. 8, indicating a rather limited variational and balancing capability. A gait with minimal adaptivity and flexibility

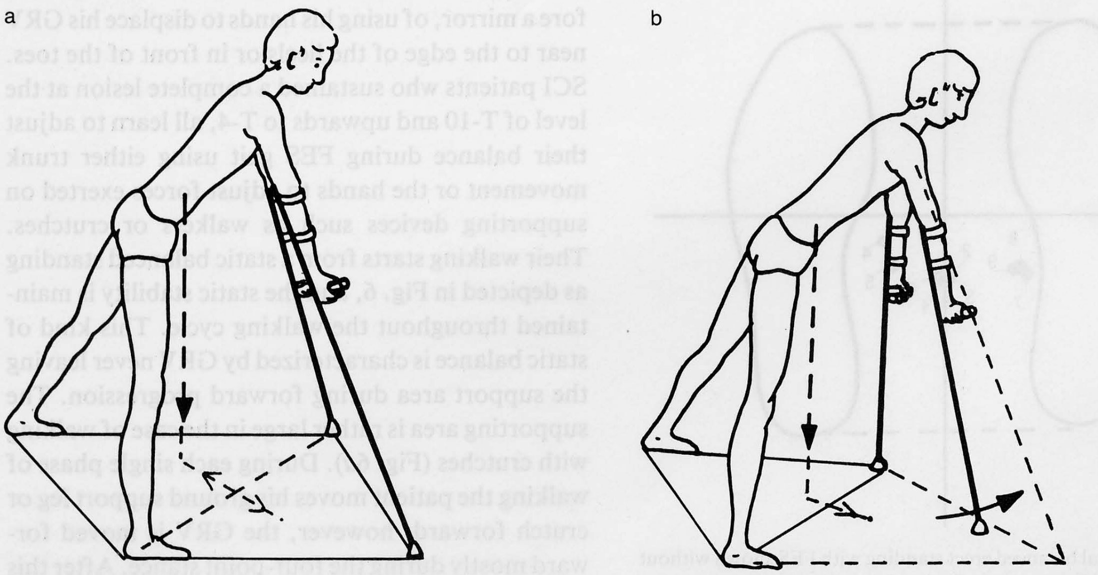


Fig. 6. Support area formed by the four-point standing. The patient is able to move the GRV within the support area using hand forces and trunk leaning to the left or right. After, for example, the crutch is moved forward, the GRV remained within the support area depicted in (*b*); the GRV position changes when the trailing leg is moved forward.

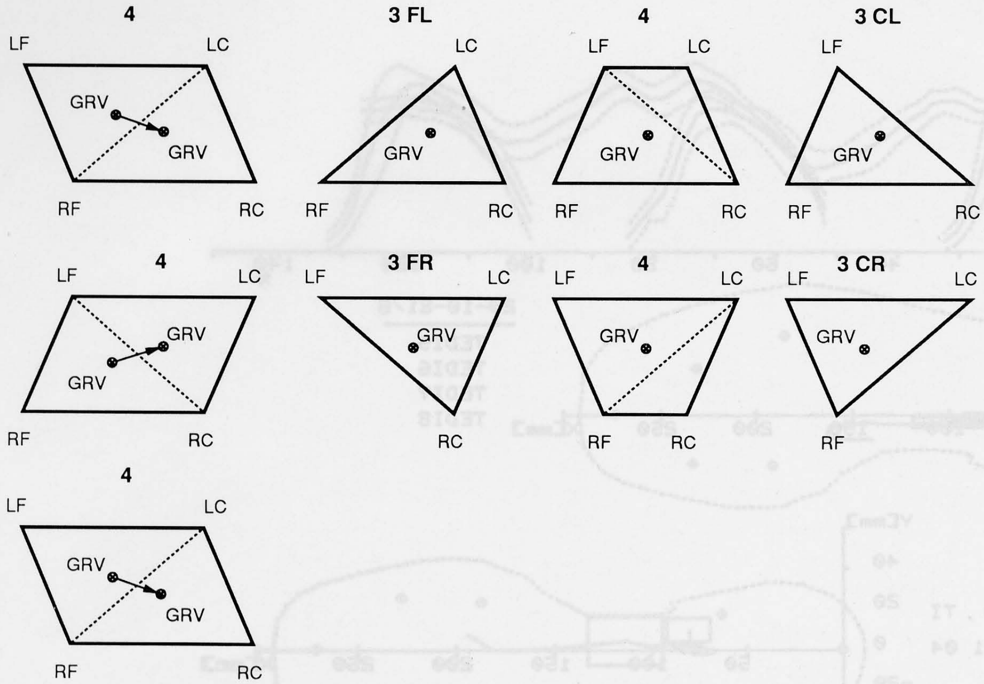


Fig. 7. Graphic presentation of gait sequences and the support areas formed during four-point FES gait. GRV is nearly stationary and relocates forward mostly during the four-point standing phase.

results. If one is interested in converting the statically balanced gait into a dynamically balanced gait, two main requirements have to be ensured: (1) active balance; and (2) for a brief time in the gait cycle the GRV should pass the boundary of an area (Raibert, 1986). Controlled falling is essential because during this time acceleration can take place, and with it potential energy can be converted into kinetic energy. After each brief period of controlled falling restabilization must take place. For this function either the FES muscle power at leg joints, or hand forces with proper crutch placement on trunk movements can be employed. There are several feasible solutions for ensuring effective stabilization by means of active balancing forces. For such gait four (or at least three) supporting points can be selected and therefore, this gait is characterized as quadrupedal. Three- or four-point support is crucial because then numerous gait modes are feasible, which presents a major advantage for SCI patients. Due to lower motor neuron damage some muscles are not available for electrical activation, and therefore the patient may have to be trained to use a different gait pattern. This selection process can only be effective when physical therapists and medical doctors advising the patient have the requisite biomechanical knowledge.

With the above goals in mind we are seeking theoretical evidence that such reciprocal quadrupedal locomotion modes exist. In addition, we are investigating the feasibility of developing a training methodology, considering indications and patients' acceptance (Bajd and Kralj, 1991). In Fig. 7, the assignment, 4, means that all four supporting elements are in contact with ground and accepting load; while 3 FR stresses that three supporting elements are in place but the right foot is unloaded and is in swing phase (Bajd and Kralj, 1991). Using such simple notation the expression for the gait in Fig. 7 can be written as:

$$4 - 3FL - 4 - 3CL - 4 - 3FR - 4 - 3CR - 4. \quad (1)$$

This expression highlights that each state is statically

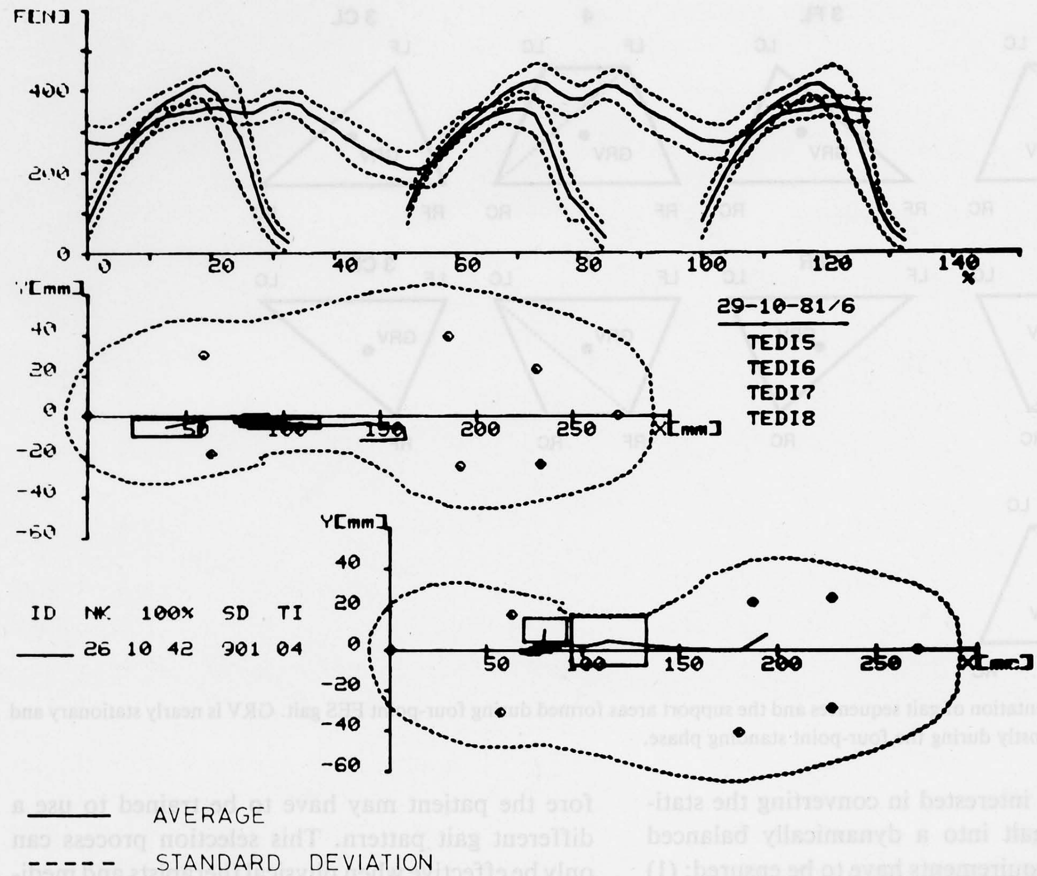


Fig. 8. Vertical component of GRV measured under each foot versus time and spatial movement of the GRV location under each foot. For the vertical component of reaction force the time dependence is displayed with corresponding standard deviation.

stable, and that there are intermittent 4-3-4 transitions. It is also interesting to compare expression (1) with that for swing-through gait in SCI patients. This gait is substantially faster compared to FES gait. Using our notation, expression (2) clearly indicates that in swing-through gait each static stable state is followed by an unstable falling state:

$$4 - 2F - 4 - 2C - 4 \quad (2)$$

Fast gait modes have to incorporate unstable states for transitions, and restabilization states where stability is ensured and propulsion generated. Expression (2) suggests that we have to modify the four-point gait of expression (1) by reducing the number of states (compare (1) with (2)) and by inserting a dynamically stable tipping phase between restabilization states. The latter state can be a four-point or three-point support state. One logical way to reduce the number of stable states in expression (1) is to combine two stable three-point phases into one unstable two-point support phase. To synthesize such a reciprocal gait pattern either the 2R (2L) or 2CRFL (2CLFR) state can be selected. This reasoning has resulted in two gait patterns: the first we may call an ipsilateral (expression 3), and the second a contralateral reciprocal gait pattern (expression 4):

$$4 - 2R - 4 - 2L - 4 \quad (3)$$

$$4 - 2CRFL - 4 - 2CLFR - 4 \quad (4)$$

Because the three-point stance phase is also statically stable, and can provide adequate stabilization in some less-damaged SCI patients, the four-point phases in expressions (3) and (4) can be substituted with three-point stance phases.

The solution for FES gait described above provides a basic hope that FES gait in SCI patients can be substantially enhanced. It is also important to note that this solution does not preclude restoration of two-legged balance. Rather it provides the patient with an immediate adequate and reasonable stabilization solution with which he can recover balance lost during the dynamically performed unbalancing. This unbalancing is necessary for faster propulsion, increasing progression velocity and more efficient energy exchange. During the static stable states which are inserted between the unstable states the lost balance and potential energy can be restored. Energy can be stored by either increasing the body's potential energy or during the unbalancing phase by accelerating the movement. The latter places increased demands on stabilization. There is a tight association between increased stabilization, actively controlled locking of joints and sensory feedback. Attention to all three aspects of this association may permit the tightly prescribed placement of legs and crutches to be relaxed so that they can be moved more freely to more distant locations, resulting in increased mobility and adaptability. Here, we do not discuss the underlying control issues. The theoretical work by Raibert (1986) provides evidence that even though the dynamics of a segmented and inherently unstable system can be rather complicated, the control rules that use this dynamics can be simple. This leaves the hope that a patient's autonomy will not be reduced with the introduction of the proposed enhanced gait modes. It is also worth pointing out that a series of preprogrammed gait sequences also limits the patient's autonomy, his flexibility and perhaps his functionality. For this reason prestored gait sequences should be avoided.

Conclusions

The restoration of reciprocal bipedal gait in SCI patients using FES is in its current state of development and technology far from being able to restore normal upright balance and stability without depending on supplementary aids such as crutches or walkers. From this point of view, FES-restored gait in SCI patients must be treated as a quadrupedal gait mode. The numerous possibilities already presented in the literature (McGhee and Kukner, 1969) are the most promising for FES explored here. Our findings indicate that SCI patients, while in FES-assisted three-point or four-point stance, are able to balance and maintain upright stability. Our findings also indicate that the current FES-restored gait relies on static stability and can be characterized as quadrupedal crawl gait, which is slow and energy-demanding. Our findings highlight the possibility of including the dynamic transfer phase to change gait from a static to a semi-dynamic mode. The static equilibrium achieved before and after each dynamic transfer ensures sufficient stability. The walking pattern can be considered as simple dynamic gait displaying all the attributes of energy exchange and conversion, and higher progression speed with capabilities of negotiating rough terrain. Further research should focus on the requirements of the unbalancing phase, generation of propulsion by FES muscles, the transfer of energy among segments, the necessary stabilization processes, and training acquired for patients to master the proposed enhanced and dynamic gait.

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