# Four-Point Walking Patterns in Paralyzed Persons

Tadej Bajd and Alojz Kralj

*From the Faculty of Electrical and Computer Engineering, University of Ljubljana*

**Abstract**

The existing walking patterns in completely paralyzed paraplegic subjects are described by the help of sequential logical expressions and graphic representations. The finite states of swing-through walking modality and FES reciprocal ambulation are analyzed. Improved FES gait patterns are proposed by introducing unstable states into the walking sequence. Such walking may result in higher speed and lesser energy demand. The importance of modelling the locomotion of completely paralyzed persons as a four-point or quadruped gait (two feet and two crutches) is stressed.
**Key words**: gait, functional electrical stimulation, paraplegia.

*BAM 1 (1): 95-100, 1991*

Walking in completely paralyzed persons can be realized by passive mechanical bracing of paralyzed lower extremities. In spinal cord injured subjects with preserved excitability of the lower motoneuron, functional electrical stimulation (FES) delivered to the efferent and afferent pathways of the peripheral nervous system can be applied. In both cases the use of crutches has to assure the upright balance and stability of walking. Multichannel FES enables reciprocal gait pattern which is closer to natural biped gait and considerably more aesthetic than swing-to or swing-through walking performed by the knees locked. In addition, FES has several physiological and psychological advantages [1]. On the other side the FES walking pattern has several limitations. Apart from fatiguing of electrically stimulated muscles, the most crucial deficiencies of FES walking appear to be low walking speed and high energy cost. The walking speed of the spinal cord injured subjects utilizing minimal four-channels FES reciprocal ambulation is for about ten times lesser than in normals [1]. The energy expenditure of current FES walking modalities, being considered as feasibility demonstration approaches, is somewhat higher than in passive long leg brace ambulation and significantly higher than in healthy subjects [2]. Improved walking speed and energy expenditure can be obtained by more efficient control over electrically actuated paralyzed muscles.

The finite-state approach to the control of rehabilitative locomotor systems was proposed as the most appropriate way to solve the problems of the man-machine interface [3]. Gait was described in terms of functional states and discrete events marking the transitions between the states. Such discrete-event control was being taken also for paraplegic walking using multichannel FES. The events that occur at the state transitions were described by logical expressions. The functional states were defined, and sensors necessary for the detection of the events were developed and evaluated [4].

Walking in completely paralyzed subjects can be restored also by the combination of passive orthotic devices and FES. In these hybrid rehabilitative systems mechanical bracing provides support to the body while the movements of single joints are provided by FES of appropriate muscles. Also here, the application of nonnumerical logical control has proved to be an efficient method for gait restoration [5]. Artificial intelligence methods were introduced in order to develop the rules indicating the transition from one state of walking into another [6].

The aim of this paper is to propose more efficient FES gait patterns than those presently used in clinical and research environment. The gait patterns should result in increased speed of walking and diminished energy cost. They will be described by sequential discrete states. The states will be defined with regard to the four-point (two feet and two crutches) nature of the paralyzed persons ambulation. The problems of gait control will be addressed from the point of view of patient's voluntary control over his walking pattern and also taking into account the process of teaching of walking performed by physiotherapist in the early stage of gait training.

## Methods and Terminology

The states of a four-point walking pattern will be simply defined by the number of contacts with the ground. In this way we are dealing with:

- four-point stance phase,
- three point stance phase, and
- two-point stance phase.

The first two phases are stable while a patient cannot remain for a longer period of time supported only in two points. One-point stance phase is in general also possible. However, it is the opinion of the authors that introducing standing on only one foot would at this stage of FES control reliability result in possible hazardous situations of completely paralyzed patient's walking.

When describing different gait patterns sequential logical expressions and graphic representations will be used. By the help of sequential logical expressions the temporal events will be described while graphic presentations will provide insight

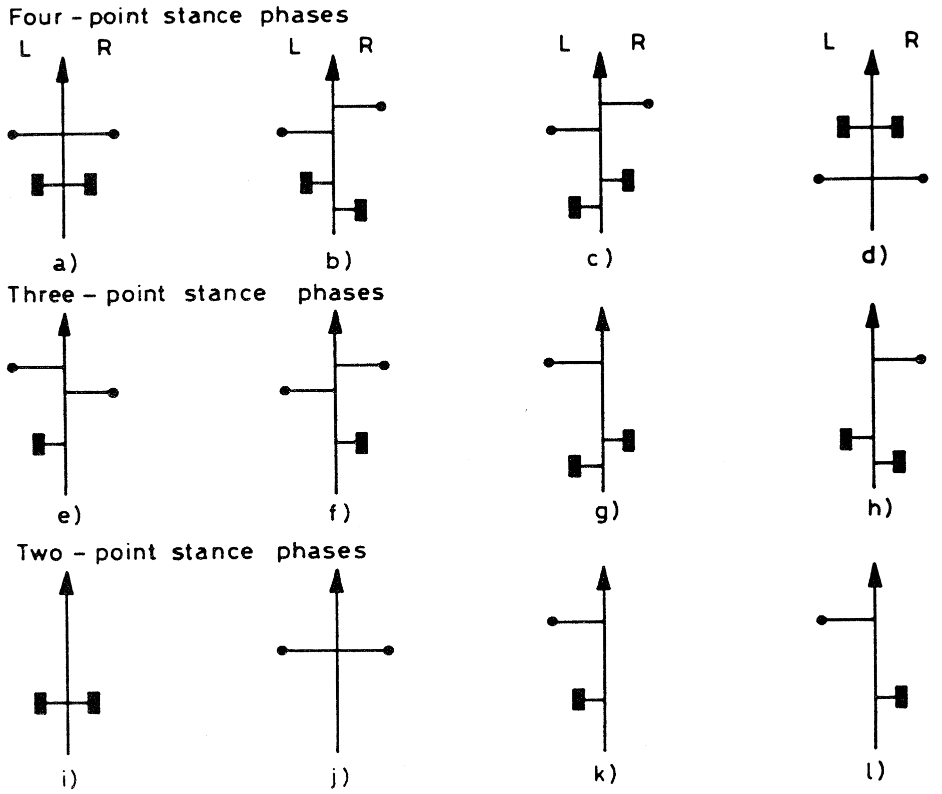


*Figure 1. Graphic representations of different states of four-point walking pattern*

into the spatial distribution of the four contact points. In both types of description of walking special symbols will be used. When writing the sequential logical expressions the symbols will consist from mnemonically chosen numbers and letters. In the graphic descriptions the approach very similar to the one proposed as early as 1887 by Eadweard Muybridge, when studying the locomotion in horses, will be applied [7]. The graphic presentation of four-point, three-point, and two-point states of walking are presented in Fig. 1. The direction of walking is represented by an arrow. The crutches are depicted by small dots while the rectangles indicate both feet. The dot and the rectangle plotted on the right side of the arrow belong to the crutch held by the right hand and to the right foot respectively. When a foot or a crutch is lifted from the ground it is simply omitted from the graphic representation. The representations do not demonstrate the exact distances between the four points of contact. They only show a general spatial relationship of both crutches and feet.

During the four-point stance phase both feet and both crutches are on the ground. This state will be, therefore, in our logical expressions denoted briefly by the number 4. Regarding the four-point stance phase from the point of view of graphic diagrams different situations can occur. Some of them are shown in the first row of Figure 1. Fig. 1a represents standing supported by the crutches being the initial position for any type of walking. The representations b and c belong to the reciprocal locomotion patterns while the last diagram shows the situation occuring during the swing through gait performed by help of crutches and long leg mechanical braces.

There are four different states possibles where the contact in three points exists. The four three-point stance phases are the following:

- 3FR...right foot from the ground
- 3FL...left foot from the ground
- 3CR...right crutch from the ground
- 3CL...left crutch from the ground

In order to deal with shorter symbols, the foot or crutch being lifted from the ground was considered. All four situations are also graphically presented in the second row of the Figure 1. The four and three-point stance phases represent stable states of walking. In these states the paralyzed person can remain for an arbitrary period of time. In contrary, the two-point stance phase describes an unstable state representing a brief transition period for the paralyzed walker. The six two-point stance phases possible are as follows:

| | |
|---|---|
| - 2C ... | both crutches from the ground |
| - 2F ... | both feet from the ground |
| - 2R ... | right crutch and right foot from the ground |
| - 2L ... | left crutch and left foot from the ground |
| - 2CRFL ... | right crutch and left foot from the ground |
| - 2CLFR ... | left crutch and left foot from the ground |

The first two unstable states (Fig. 1 i and j) are occurring during the swing-through walking of paralyzed persons. The states 2R and 2CRFL are shown in Fig. 1 k and l respectively.

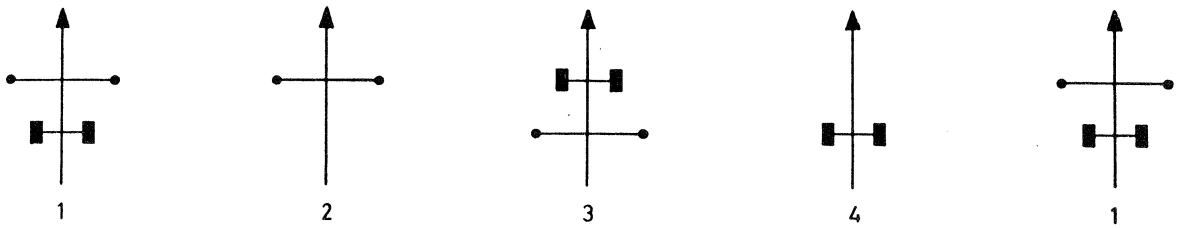


*Figure 2. Graphic representation of swing-through walking pattern*

**Existing Four-Point Walking Patterns**

A completely paralyzed person can walk either by the help of mechanical fixation of the lower limb or by the use of multichannel FES delivered to the paralyzed muscles. In the first case the long-leg braces or so called calipers, providing locking of the knee joint in extended position and ankle joint in neutral position, are the most commonly used appliance for most patients [8]. The swing-through gait is the fastest and most useful gait pattern of the completely paralyzed persons using long-leg braces and crutches.

The initial position is characterized by both crutches placed forward (Figure 2.1). Patient is leaned forward and the weight is partially carried by the hands and arms. Then the walking person must push down on the hands, extend the elbows, adduct the shoulders and lift the trunk and both legs. In this way the walking subject is providing the potential energy which is later during the swing phase converted into the kinetic energy. The subject is for a short period of time in an unstable state supported only by the two crutches (Fig. 2.2). The lift must be sustained until the legs have swung forwards (Fig. 2.3). When the weight is again firmly on the feet, patient can lift both crutches simultaneously (Fig. 2.4) and, being again in an unstable state, move them forward in order to control the stability and momentum of walking. During this braking phase of swing-through gait most of the kinetic energy is dissipated by the shoulders and new potential energy must be provided for the next step. The events occuring during the swing-through walking can be described in the form of the following logical sequential expression:

$$4 \rightarrow 2F \rightarrow 4 \rightarrow 2C \rightarrow 4 \quad (1)$$

The equation (1) indicates that there are four states necessary to synthesize the locomotion in subjects with the totally paralyzed lower extremities. In Fig. 3 a paraplegic person is presented while being in the 2F state of the swing-through walking.

The reciprocal FES walking pattern can be realized by a minimum of four electrical stimulation channels [1]. During walking the stimulator is controlled by the patient through two hand switches attached to the handles of both crutches. When neither of the switches is pressed, both knee extensors are stimulated, thus locking both knees in fully extended position. On pressing the switch in the right hand, the right leg is stimulated to flex. The same is true for the left leg. The flexion of the paralyzed limb is accomplished through withdrawal reflex triggering. The duration of the flexion reflex triggering is equal to the time of pressing the hand switch.

The four-channel FES gait can be described by the following

*Figure 3. Completely paralyzed paraplegic person while walking by the help of crutches and long-leg mechanical braces*

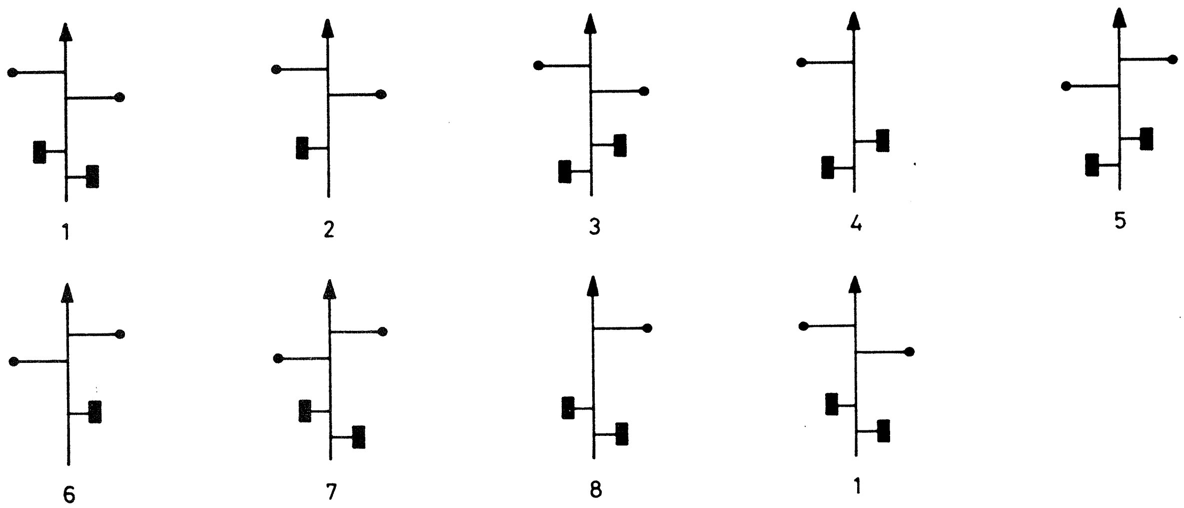


*Figure 4. Graphic representation of reciprocal FES walking pattern*

logical sequential expression:

$4 \rightarrow 3FR \rightarrow 4 \rightarrow 3CR \rightarrow 4 \rightarrow 3FL \rightarrow 4 \rightarrow 3CL \rightarrow 4$ (2)

Eight different states are necessary to describe the FES walking pattern. From the equation (2) it can be observed that a paralyzed person, when changing from one state into another, only moves one crutch or one foot at a time. Each single move of a crutch or a foot is followed by the four-point stance phase. No unstable states are used within the reciprocal FES assisted ambulation. The graphical representation of the reciprocal FES gait pattern is shown in Fig. 4. A completely paralyzed paraplegic patient while being in the 3FL state is presented in Fig. 5.

When comparing both walking patterns described, it can be first stated that simultaneous lifting of both legs during the swing-through gait is rather unnatural way of biped locomotion. Sequential lifting of the body followed by muscular braking during the feet landing phase is characterized also by high energy expenditure. Therefore, the paraplegic patients who require two long-leg braces usually do not continue to walk after discharge from a rehabilitation unit [9]. Reciprocal movements bring some more aesthetics into the FES walking pattern. Also here, 37% of independent walkers abandoned FES when returning to the home environment [1]. FES walking is even more energy demanding. The energy collected during each three-point stance phase is lost in the subsequent four-point stance phase. The conservation of energy between two successive steps, through transformation of potential into kinetic energy and back to potential, is one of the main characteristic properties of normal biped walking and is absent in presently used FES assisted walking.

From the Fig. 2 it can be observed that the swing-through walking pattern includes two unstable states. These are the states 2F and 2C when either both feet or both crutches are from the ground. In contrary, the reciprocal FES gait pattern consists of stable states only. Different types of three point stance phases are always followed by a four-point stance phase. The comparison of the two existing walking modalities suggests that unstable states are to be introduced also into the FES reciprocal walking pattern if faster and more efficient walking is to be achieved.

*Figure 5. Completely paralyzed paraplegic person while walking by the help of crutches and four-channel electrical stimulation*

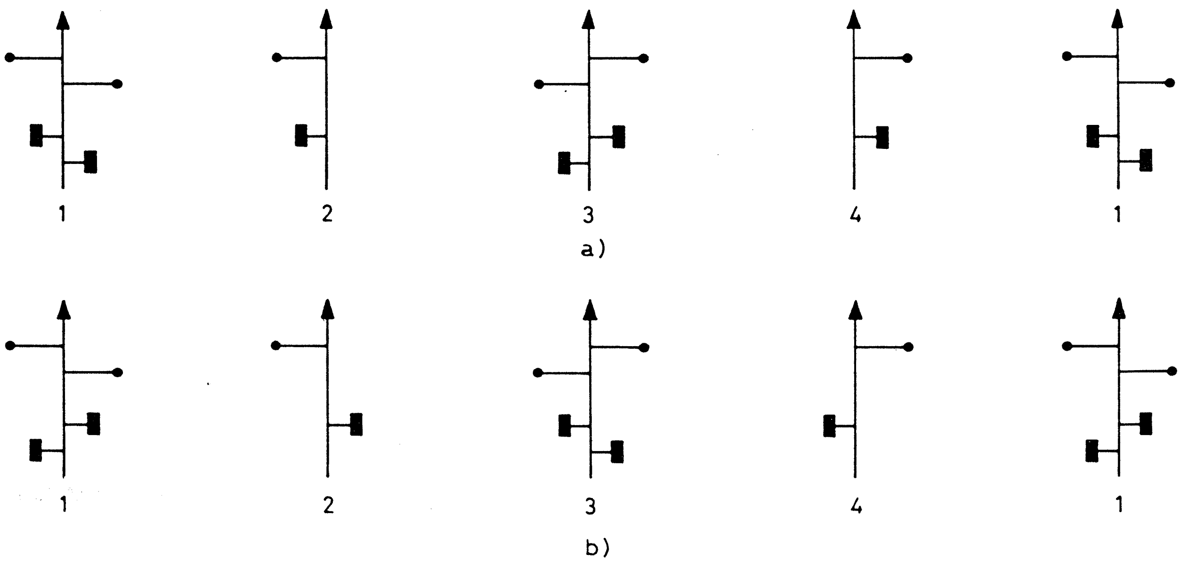


*Figure 6. Ipsilateral (a) and contralateral (b) reciprocal FES walking patterns*

**Improved FES Walking Patterns**

Faster FES gait can be obtained by decreasing the number of the states in the expression (2). This can be achieved by combining two stable three-point stance phases into one unstable two-point contact phase. As it is our aim to preserve the reciprocal walking pattern either the 2R(2L) or 2CRFL (2CLFR) state can be selected. In this way we are dealing with two different FES gait patterns. The first modality can be named ipsilateral reciprocal walking pattern and is described by the following sequential logical expression:

$$4 \rightarrow 2R \rightarrow 4 \rightarrow 2L \rightarrow 4 \qquad (3)$$

Here again, only four different states are encountered. The paralyzed person must lift simultaneously the ipsilateral crutch and foot while shifting for a short time interval the body weight to the supported side. The four-point stance phase introduced between the two unstable states provides sufficient security to the paralyzed person. The ipsilateral reciprocal walking is to some extent similar to the normal biped locomotion where the body weight is alternately transferred from one side onto another. This pattern can be found also in a normal man, when observing the temporal relations between walking and swinging of the arms. The graphical presentation of the gait pattern proposed is shown in Fig. 6a.

By introducing the 2CRFL (2CLFR) state between two stable four-point stance phases the contralateral reciprocal FES walking pattern is obtained. It can also be described by four different states:

$$4 \rightarrow 2CRFL \rightarrow 4 \rightarrow 2CLFR \rightarrow 4 \qquad (4)$$

The graphical representation in Fig. 6b belongs to the sequential logical expression (4). Because of the contralateral support the transfer of the body weight between the lower limbs will be less pronounced. Smoother trajectory of the center of body weight in the transverse plane of walking may result in more energy efficient walking.

The four-point stance-phase, such as introduced into the gait patterns proposed in Fig. 6a and b, is not always necessary. Sufficient support of the body can be in adequately trained SCI subjects provided by a three-point stance phase. The resulting gait pattern becomes very similar to that found in walking of quadrupedal animals. The pattern described by the logical expression (5) will be, therefore, named quadruped walking pattern:

$$3CR \rightarrow 2CRFL \rightarrow 3CL \rightarrow 2CLFR \rightarrow 3CR \qquad (5)$$

The quadruped walking is schematically presented in Fig. 7. Here, it must be noted that similar pattern of feet and hands movements occurs also in children while crowling on all four extremities.

By comparing the expression (3), (4), and (5) it can be observed that all three improved FES gait patterns proposed can be described by four different states. The same number of the states was necessary also in the logical description of the swing-through walking with mechanical long-leg braces (1). Lesser number of the states can be obtained only in the case when a paralyzed person changes one unstable state directly by another unstable state. Such walking patterns are in general not impossible. However, it is the opinion of the authors that first the walking patterns proposed in this paper must be experimentally introduced and carefully evaluated through adequate kinesiological assessments.

**Discussion**

There are two important conclusions that can be redrawn from the present paper:

1. The FES restored walking in completely paralyzed persons is to be treated as a four-point or quadruped locomotion.

2. Unstable states are to be introduced into the FES walking pattern in order to achieve faster and more energy efficient

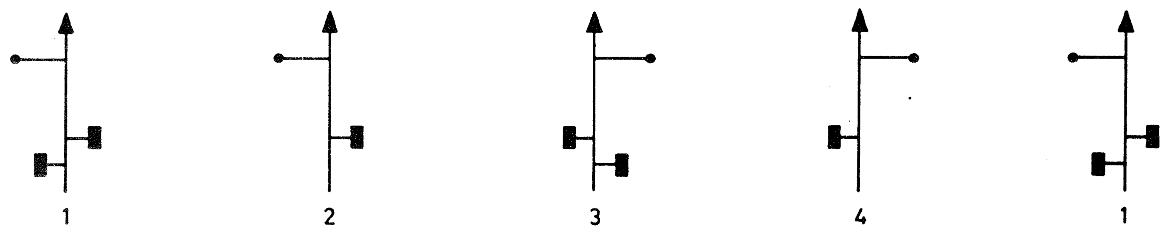


*Figure 7. Quadruped FES walking pattern*

ambulation.

It is difficult to believe that the balance and stability problems of a biped actuated through electrically stimulated paralyzed muscles will be satisfactorily solved in a near future. The completely paralyzed paraplegic patients are, therefore, forced to use crutches. This characteristic property of their walking significantly influences the development of kinematic and dynamic models which are necessary in planning of the appropriate control of a multichannel FES stimulator.

Voluntary patient's control over the FES rehabilitative device is necessary because of uneven grounds and many different obstacles encountered both in man-made and natural environment. This control is represented by voluntary transition from one state of walking into another. Decreasing the number of the necessary states of a walking pattern may result in a higher speed of walking. The reducement of the number of states can be achieved by introducing the unstable states. The unstable states provide the possibility of energy conservation between two successive steps. From the other point of view introducing unstable states into FES walking pattern may require more than four channels of electrical stimulation. Additional stimulation channels will be needed in order to provide stabilization of pelvis in both sagittal and lateral plane. This task can be efficiently accomplished through electrical stimulation of hip extensors and hip abductors.

Let us in conclusion make a comparison between the locomotor rehabilitation and robotic manipulation. When introducing a robot manipulator into an industrial process, both efficient robot control and teaching are necessary for successful accomplishement of a robot task. The teaching of a robot is performed with the help of appropriate transducers and friendly software by the human operator. The same is valid also for the rehabilitation process of walking by the help of multichannel FES. Considerable research efforts were directed towards the improvement of gait control [3-6] while teaching of different FES assisted gait patterns was not considered. This teaching is performed by physiotherapist according to the rules and knowledge derived from the restoration of ambulation in incompletely paralyzed persons. The bioengineering principles are to be introduced also into this very important part of the locomotor rehabilitation.

**Address correspondence to:**

Dr. Tadej Bajd, Faculty of Electrical and Computer Engineering, University of Ljubljana, 61000 LJUBLJANA, Trzaška 25, YUGOSLAVIA

**References**

[1] Kralj AR, Bajd T. *Functional Electrical Stimulation: Standing and Walking after Spinal Cord Injury.* Boca Raton, FL: CRC Press, Inc., 1989; pp 1-198.

[2] Marsolais EB, Edwards BG. "Energy costs of walking and standing with functional neuromuscular stimulation and long leg braces", *Arch. Phys. Med. Rehabil.*, 1988; 69: 243-249.

[3] Tomovic R, McGhee RB. "A finite state approach to the synthesis of bioengineering control systems", *IEEE Trans. on Human Factors in Electronics,* 1966; 7: 122-128.

[4] Chizeck HJ, Kobetic R, Marsolais EB, Abbas JJ, Donner IH, Simon E. "Control of functional neuromuscular stimulation systems for standing and locomotion in paraplegics", *Proc. of the IEEE*, 1988; 76: 1155-1165.

[5] Popovic D, Tomovic R, Schwirtlich L. "Hybrid assistive system - The motor neuroprosthesis", *IEEE Trans. Biomed. Eng.*, 1989; 36: 729-736.

[6] Andrews BJ, Barnett RW, Phillips GF, Kirkwood CA. "Rule-based control of a hybrid FES orthosis for assisting paraplegic locomotion", *Automedica*, 1989; 11: 175-199.

[7] Muybridge E. *Animals in Motion.* New York, Dover Publications, Inc., 1957; pp 1-57.

[8] Bromley I. *Tetraplegia and Paraplegia.* Edinburgh; Churchill Livingstone, 1981, pp 1-256.

[9] Waters RL, Yakura JS. "The energy expenditure of normal and pathological gait", *Critical Reviews in Physical and Rehabilitation Medicine*, 1989; 1: 183-209.