Unstable states in four-point walking

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ABSTRACT

The presently utilized walking patterns in paraplegic subjects with complete spinal cord injury (SCI) are compared by the help of graphic representations. Improved four-point gait assisted by functional electrical stimulation (FES) and crutches is proposed by introducing unstable states into the walking sequence. The unstable states are defined as passive phases of walking where the centre of mass (COM) is gravity driven in the direction of progression. The unstable state is described by a simple inverted pendulum model. Kinematic measurements of the unstable state were performed in normal and paraplegic subjects.

Keywords: Functional electrical stimulation, paraplegia, gait

INTRODUCTION

Mobility of paraplegic subjects with complete spinal cord injury (SCI) is mostly confined to the wheelchair. Limited walking can be realized in selected paraplegics either by passive bracing of lower extremities or by active assistance using multichannel functional electrical stimulation (FES) delivered to the lower limb muscle groups. In both cases the equilibrium has to be provided by the use of crutches. It is unlikely that the balance problems will be solved in the near future. Restored walking in completely paralysed persons is treated as four-point locomotion. 'Swing-though' gait is the fastest and most useful gait pattern of the spinal cord injured subjects using passive long-leg braces. In the initial position, the walking subject leans forward on the crutches while the body weight is partially carried by the hands and arms. Then the subject must push down on the hands, extend the elbows, adduct the shoulders and lift the trunk and both legs. For a short period of time, the subject is in an unstable state, being supported only by the two crutches. The lift must be sustained until the legs have swung forwards. When the body weight is again firmly transferred to the feet, the patient can lift both crutches simultaneously and, being again in an unstable state, move them forward in order to maintain equilibrium.

Reciprocal FES aided walking patterns can be produced by a minimum of four electrical stimulation channels[1]. During walking the stimulator is controlled by the patient through two push buttons built into the handles of both crutches. When neither of the push buttons is pressed, both knee extensors are stimulated, locking the knees in the fully extended position. The subject remains in the double stance phase of walking with support provided by both legs and both crutches. On pressing the push button in the right crutch, the right leg is stimulated to flex. The subject enters the right swing phase of walking when he is supported by one leg and both crutches. The sequence is repeated for movement of the left leg. The flexion of the limb is accomplished by eliciting a withdrawal reflex; this flexion reflex is activated by pressing the crutch push button and ceases on release of this button.

Graphic representations[2] of the 'swing-through' walking pattern and the reciprocal FES walking pattern are shown in *Figure 1*. The direction of progression is represented by the arrow. The crutches are depicted by dots while the rectangles indicate both feet. When a foot or a crutch is lifted from the

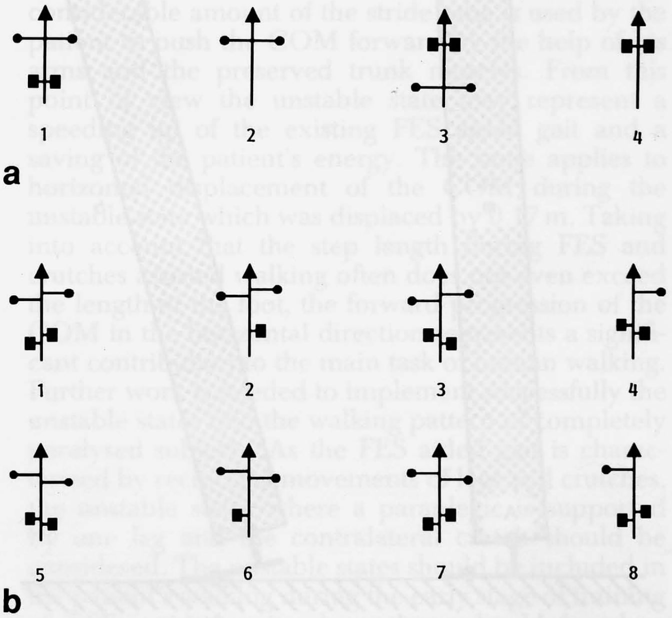

Figure 1 **a**, Representation of 'swing-through' walking and **b**, reciprocal FES assisted walking pattern. The crutches are represented by dots and the feet by rectangles

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ground it is omitted from the graphic representation. The representations are not to scale, but show the general spatial relationship of both crutches and feet.

The most noticeable difference between the gait patterns presented in *Figure 1* is reflected in the unstable states included in the 'swing-through' walking pattern. These are the states 2 and 4 in *Figure 1a* when either both feet or both crutches are lifted from the ground. During the unstable state 4 the centre of mass (COM) is driven by gravity and inertia[3] and not by the patient's muscular energy. This is in contrast to the reciprocal FES pattern consisting of the stable states only. In the FES gait pattern described, pushing the COM forward is performed by the help of arms and preserved trunk muscles. The comparison of the two existing walking modalities suggests that the unstable states in the FES walking pattern may produce faster and more efficient walking.

METHODS

Development of the model

A simple model was developed to simulate the experimental conditions for assessing the COM movement during the unstable state. Of special interest is the duration of the passive movement and the horizontal displacement of the COM in the sagittal plane. The inverted pendulum has often been used as one of the simplest models of stable upright posture[4,5] or biped locomotion[6]. In our study the body is represented by an inverted rectangle with a mass m of 75 kg, height b of 1.80 m and width a of 0.15 m. It was assumed that the hip joints are locked in the hyperextended position while the knee joints are fully extended by the help of FES delivered to the quadriceps muscle groups. The simple model of the unstable state is graphically represented in *Figure 2*. At the commencement of the unstable state the body rotates around the ankle joint (point A in *Figure 2*). The movement of the inverted pendulum can be described by the following differential equation:

$$J_1\vartheta'' + B\vartheta' + k\vartheta + M_{\mathrm{fr}} - (mg/2)\sin\vartheta = 0. \qquad (1)$$

B and k are related to the viscoelastic properties of the ankle joint[7] The parallel viscous damping, $B = 3.8\ \mathrm{Nm\,s\,rad^{-1}}$ is the sum of the viscous parameters of the joint and the agonist and antagonist muscle groups. The elasticity of both muscle groups governing ankle joint movement, is represented by $k = 7.5\ \mathrm{Nm\,rad^{-1}}$ The Coulomb friction, $M_{\mathrm{fr}} = 1.2\ \mathrm{Nm}$ was also included in the model. The inertia of the rectangle rotating around the ankle joint is $J_1 = (m/12)(a^2 + b^2)$.

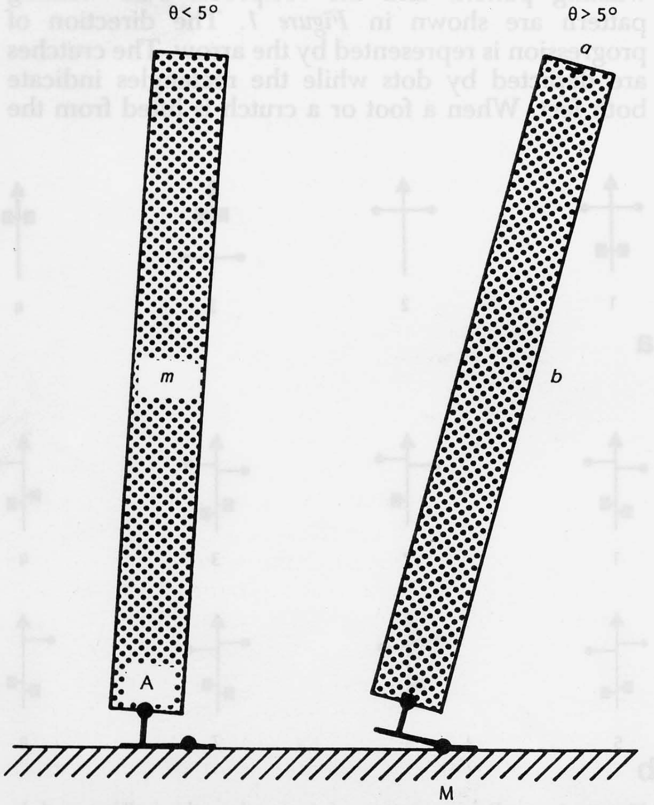

Figure 2 Mechanical model of an inverted pendulum used to simulate the unstable states

At larger angles of the body, rotation around the metatarsal joints occurs. In *Figure 2* the metatarsal joints are depicted by the point M. With regard to the frame of reference the start of the rotation about point M is given by:

$$\vartheta = \mathrm{arctg}\,(a/b). \qquad (2)$$

In our simple inverted pendulum model the starting condition approximately corresponds to $\vartheta = 5°$. As the muscles around the metatarsals are considerably smaller in bulk than those around the ankle joint, the viscoelastic properties of the metatarsal joints were neglected. For inclinations greater than 5°, the following equation was used:

$$J_2\vartheta'' + (gm/2)(a\cos\vartheta - b\sin\vartheta) = 0. \qquad (3)$$

The inertia for $\vartheta > 5°$ was $J_2 = (m/3)(a^2 + b^2)$. By simultaneously resolving equations (1) and (3), the time course of the horizontal COM displacement could be calculated. The computed curve is shown in *Figure 3*. The block started to fall at the initial condition $\vartheta(0) = 10°$, and the unstable state was stopped at $\vartheta = 30°$; It was seen from the time plot that the duration of the unstable state was approximately 1 s; in this time the COM moved forward by 0.27 m in the horizontal direction of progression.

Instrumentation and measurements

The COM displacement was measured by the use of a contactless measuring system called 'V-scope'[†]. This system consists of three stationary infrared/

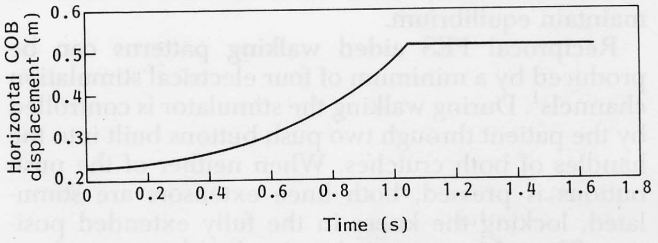

Figure 3 Computed curve of the horizontal displacement of the centre of mass (COM)

[†] Model VS-100, Litek Advanced Systems, Ltd., P.O. Box 13261, Tel Aviv, Israel

ultrasound transceivers placed in the space around the measured subject. Small infrared/ultrasound markers are attached to the part of the body to be observed. In the present investigation only two markers were used: the first was attached in the approximate position of the COM in the sagittal plane with the second at the approximate centre of the ankle joint rotation. In adult humans the COM is located at the height of the second sacral vertebra[8]. The centre of ankle joint rotation was approximated by the point of intersection of two lines, one going through the centre of talus and toe tips, the second through the centre of talus and knee joint centre[7]. The initial position of these markers permitted the assessment of the initial inclination of the body. The V-scope system was controlled by a personal computer and displayed the marker motion immediately after the test. The sampling rate was approximately 100 measurements per second and the resolution was less than 0.5 mm.

The COB displacement during the unstable state was repeatedly measured in healthy subjects and a paraplegic patient. The twenty-five year old paraplegic subject (T-10, 11 complete injury to spinal cord, motor vehicle accident, 5 y post injury, weight 73 kg, height 178 cm) was an excellent walker when assisted by four-channel electrical stimulation[1] and crutches. He had been using an FES rehabilitative system daily already for four years.

The unstable state was assessed by the pattern of horizontal displacements of the COM. When investigating the unstable state, the subject was asked to stand with both feet and both crutches on the ground; the distance between feet and crutches was arbitrarily chosen by the subject when standing comfortably. The subject was then asked to lift both crutches, swing them forward, and put them down as he would during normal 'swing-through' walking. The knee joints of the paraplegic patient were fully extended by the help of FES delivered to both knee extensors. The measurement of the COM displacement was carried out during the transfer of both crutches from the initial into the final position.

RESULTS

The time course of the COM along the horizontal axis in the sagittal plane in the paraplegic and a normal height-matched subject are presented in *Figure 4*. In both cases the initial inclination of the body was approximately 10°. The unstable state was provoked by simultaneous transfer of both crutches. In the displacement curve of the paraplegic, there is an irregularity occurring because of instability of the trunk possibly due to the mixed, flaccid and spastic paralysis of several long body muscles. The duration of the unstable state in both cases slight exceeds 1 s, which correlates well with that predicted by the simple inverted pendulum model. The magnitude of the horizontal COM displacement is larger in the normal subject than that calculated by the model (0.33 m compared with 0.27 m). The paraplegic was less successful in executing the unstable state resulting in a smaller amplitude of the horizontal displacement, never exceeding 0.17 m. It is also interesting to note that vertical drop of the COM during the unstable state was 0.05 m in the normal subject and 0.04 m in the paraplegic.

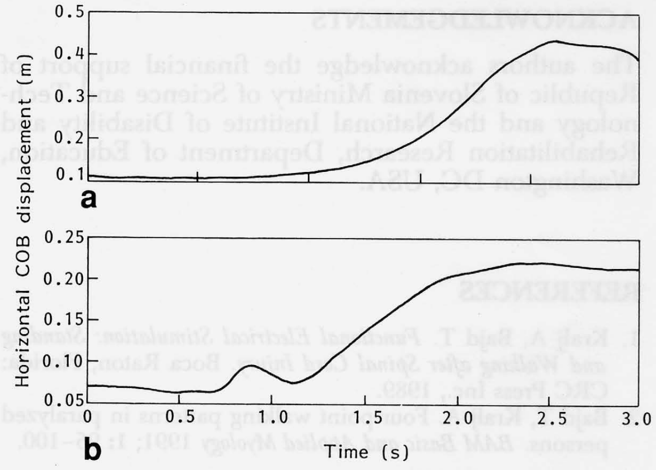

Figure 4 Horizontal displacement of the COM as assessed **a,** in a normal subject and **b,** in a paraplegic subject during simultaneous transfer of both crutches

CONCLUSIONS

Unstable states may exist in the FES aided walking pattern in order to achieve faster and more energy efficient walking using crutches. These unstable states were defined as passive phases of gait when the COM is gravity driven in the direction of progression. Kinematic assessment of the unstable state was performed. The duration of the unstable state correlated well with the simple inverted pendulum model proposed and was found to be approximately 1 s. When comparing this result to normal walking, the duration of the unstable state appears to be rather long as a whole step can be accomplished in this time by a normal person. However, the duration of stride time in the complete paraplegic subject when walking aided by the use of FES and crutches exceeds 4 s[1]. A considerable amount of the stride time is used by the patient to push the COM forward by the help of his arms and the preserved trunk muscles. From this point of view the unstable state may represent a speeding up of the existing FES aided gait and a saving of the patient's energy. The same applies to horizontal displacement of the COM during the unstable state which was displaced by 0.17 m. Taking into account that the step length during FES and crutches assisted walking often does not even exceed the length of the foot, the forward progression of the COM in the horizontal direction represents a significant contribution to the main task of human walking. Further work is needed to implement successfully the unstable states into the walking pattern of completely paralysed subjects. As the FES aided gait is characterized by reciprocal movements of legs and crutches, the unstable states where a paraplegic is supported by one leg and the contralateral crutch should be considered. The unstable states should be included in the patient's walking during the early stage of training of FES assisted gait where there should be close collaboration between the physiotherapist and the bioengineer.

ACKNOWLEDGEMENTS

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