PRELIMINARY STUDIES OF SWING-THROUGH GAIT USING FES

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ABSTRACT

Swing-through gait can be fast and efficient but can only be used by a limited number of low level paraplegic patients, with braced knees. It is proposed that using electrical stimulation will extend the patient population to whom this gait is applicable and improve the efficiency and speed compared to fixed knee bracing. It is shown that swing- through gait with knee flexion during the swinging phase can be produced using FES in the 2 subjects studied. An increased stride length is demonstrated with both subjects and an increase in speed with one subject compared with swing-through gait using conventional caliper bracing.

KEY WORDS: Swing-through, FES, gait, control

INTRODUCTION

Functional Electrical Stimulation (FES) has been used extensively for the synthesis of 4 point reciprocating gait [1,2]. However, for the mid-thoracic paraplegic this gait is slow, typically 0.14m/s [3] to 0.4m/s [1]. The 'walking' pattern generated is generally quasi-static with a short step period followed by a long stance period and could perhaps better be described as 'stepping'. Work is done during the stance phase which does not produce forward motion, hence the gait is energy consuming [3] and constrained by muscle fatigue. This type of gait has limited functional use and its' primary clinical role has been that of exercise.

Swing-through gait is a dynamic gait and so is fast [4]. There is some conservation of mechanical energy throughout the gait cycle and thus it is potentially more efficient. For those paraplegics who can perform swing-through well it is often the gait of choice.

The application of FES could enable the synthesis of swing-through gait in mid-thoracic paraplegic subjects who ordinarily would not be able to use this type of gait. FES swing-through gait can be achieved by stimulation of the relevant muscle groups plus the use of minimal additional bracing.

Problems with this type of gait so far have been:

1. The need to brace the knees either mechanically, by means of bulky and heavy Knee-Ankle-Foot Orthoses (KAFO's) or electrically by stimulation of the extensor group [5,1]. Electrical bracing results in fatigue of the quadriceps becoming the limiting factor, due to the need to keep the quadriceps stimulation permanently on throughout the gait cycle.
2. The high upper limb effort required to produce ground clearance during the swing phase. This leads to rapid fatigue and possible long term shoulder joint damage.
3. Poor cosmesis. It is not a natural looking gait and is disliked for this reason by a number of patients.

Due to these considerations, many low level paraplegics reject this type of gait in favour of the slower 4-point gait or more commonly wheelchairs.

A project has been underway at the University of Strathclyde, since October 1989, to investigate the use of FES for synthesising swing-through gait. It was proposed that:

1. By using FES to control swing-through gait the amount of energy needed to raise the centre of gravity of the body for ground clearance could be reduced. This would be achieved by flexing the knees during the swinging period of the gait by means of stimulating the flexion withdrawal response and the knee flexors.
2. By using FES to brace the trunk and stabilise the hip paraplegics with higher lesion levels would be able to perform this type of gait.
3. By providing active hip flexion the stride length could be increased so improving the speed and efficiency of the gait.

METHOD

Subjects

Subject A was a 28 year old female who had sustained a complete injury at level T11 due to a road traffic accident 6 years previously. This subject could perform 4-point gait with crutches under supervision, and with a rolator without supervision. She could perform swing-through gait independently using a rolator and KAFO's.

Subject B was 22 year old male who had sustained a complete injury at the level of T6 due to a road traffic accident 5 years previously. This subject was able to perform swing-to gait using KAFO's and a rolator, but only for limited distance under supervision.

Both subjects had undergone an FES muscle strengthening regime and had participated in previous FES standing projects. Subject A had used FES for reciprocating gait. No specific training in swing-through gait had been given since their hospitalisation. Both were capable of standing with FES alone for a least five minutes and could walk reciprocally using FES (Table 1.).

Gait Synthesis Surface FES techniques were used and gait was synthesised using the Strathclyde programmable stimulator [6].

Gait control software was developed based on the use of the finite state technique, where the gait is divided into discrete states [7]. Stimulation was applied to the quadriceps, glutei, erector spinae and peroneal nerve. Peroneal stimulation was used for hip and knee flexion. Each swing cycle was initiated by the patient. The gait cycle was divided into five states and these are defined in fig 1. Transition between phases was initially based on intuitively derived time delays. These were monitored by overlaying stimulation and sensor information onto a video of the patient walking, then optimised.

The software allowed the alternation of modes between swing-through and reciprocating gait. The user could select the appropriate mode for the conditions encountered.

A Floor Reaction Orthosis (FRO) controller [8] was incorporated using force sensitive resistors [9] to determine when the ground reaction vector passed in front of the knee during stance. This allowed stimulation of the knee extensors to be turned off, so reducing their stimulation duty cycle and hence their fatigue.

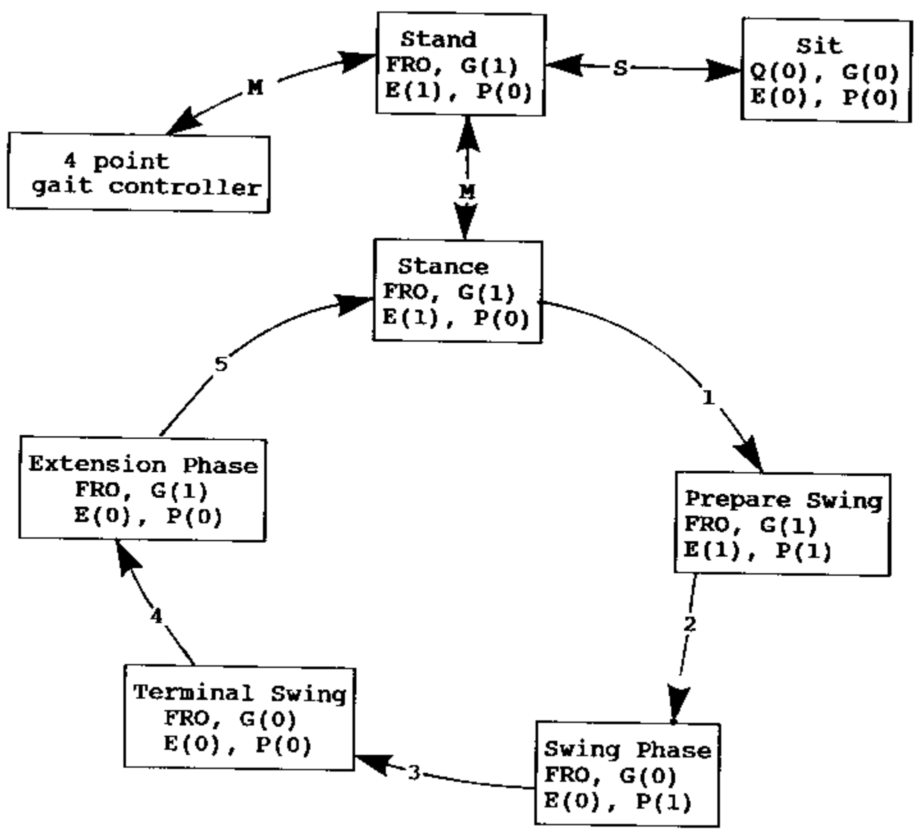
For both subjects a direct comparison was made between swing-through gait with FES alone and swing-through gait with KAFO's alone. For subject A, who had been trained in FES recprocating gait a direct comparison was made between the two modes of FES gait.

RESULTS AND DISCUSSION

	Speed (m/s)		Stride Length (m)		Cadence (strides/min)	
Gait Mode	Subject A	Subject B	Subject A	Subject B	Subject A	Subject B
non-FES swing-through	0.12	0.24	0.47	0.49	15.3	29.4
FES swing-through	0.19	0.19	0.59	0.74	19.3	15.4
FES reciprocating	0.12	N/A	N/A	N/A	N/A	N/A

Table 1

Swing-through gait has been synthesised previously using FES, but these investigators have used ES to brace the knee throughout the gait cycle. This required the input of work to raise the body during the swing phase of the gait, which could only be done by the arms which are ill-adapted to this task.



Q = Quadriceps, G = Glutei
P = Peroneal, E = Erector Spinae
0 = OFF, 1 = ON
FRO = FRO knee controller (or quadriceps stimulation)

Exit Rules for states

M = Mode selection made by key input or swtich
S = Key input
1 = Switch
2 = Delay for latency of peroneal response
3 = Time delay for swing phase
4 = Time delay for knee extension
5 = Time delay for hip extension before next swing phase

Fig 1. Finite state controller for swing-through gait

Using our method of application the knees are flexed during the swing phase of gait (fig 2d), reducing the vertical displacement that the centre of gravity has to be moved through in order for the feet to clear the ground. This reduces the upper limb effort required.

By stabilising the trunk with FES the use of swing-gait can be extended to mid-thoracic paraplegic patients.

Active flexion of the hip produced by stimulation of the flexion withdrawal response and stimulation of knee extensor group at the end of the swing phase produces an increase in the stride length (fig. 2d and 2e).

Subject A had an increase in stride length (26%) and cadence (26%) leading to an large increase in speed (58%). This speed is also equally high when compared to FES reciprocating gait. Whilst this speed is still not fast it represents a very early stage in the development of this mode of gait. We would anticipate similar increases as the subject progresses onto crutches and she achieves better familiarity with and control of swing through-gait.

Subject B also exhibited a large increase in stride length (51%) but the reduction in cadence led to a net reduction in speed (21%). The reason for this reduction in cadence can be seen from figures 2e and 2f. The stride is long enough for the subjects feet to be ahead of his centre of gravity (a necessary condition for swing-through), however, because the rolator has a high mass and is awkward to manoeuver, the momentum obtained is not sufficient to maintain forward progression. This results in the subject reaching a static position in which he is leaning backwards and from which he finds it hard to recover, leading to the sizable in cadence. The replacement of the rolator with crutches should allow the maintenance of forward progression throughout the gait cycle.

Swing-through gait is suitable for covering straight line distances quickly on even surfaces. It is inappropriate for uneven surfaces or situations requiring the negotiation of obstacles or where space is limited. In these circumstances the user can select the reciprocating mode which offers improved manoeuverability and stability at a cost to speed.

FUTURE WORK

EMG studies

Our initial synthesis of swinging patterns of gait using finite state machines has relied on simple, intuitive rules to determine the state transitions, this approach is acceptable for preliminary applications but will be inadequate for a full implementation of the gait. A parallel study is analysing the EMG timing signals of normals who have undergone training for swing-through gait. These patterns will enable the automatic induction of state transition events and define the optimal sensor set [10].

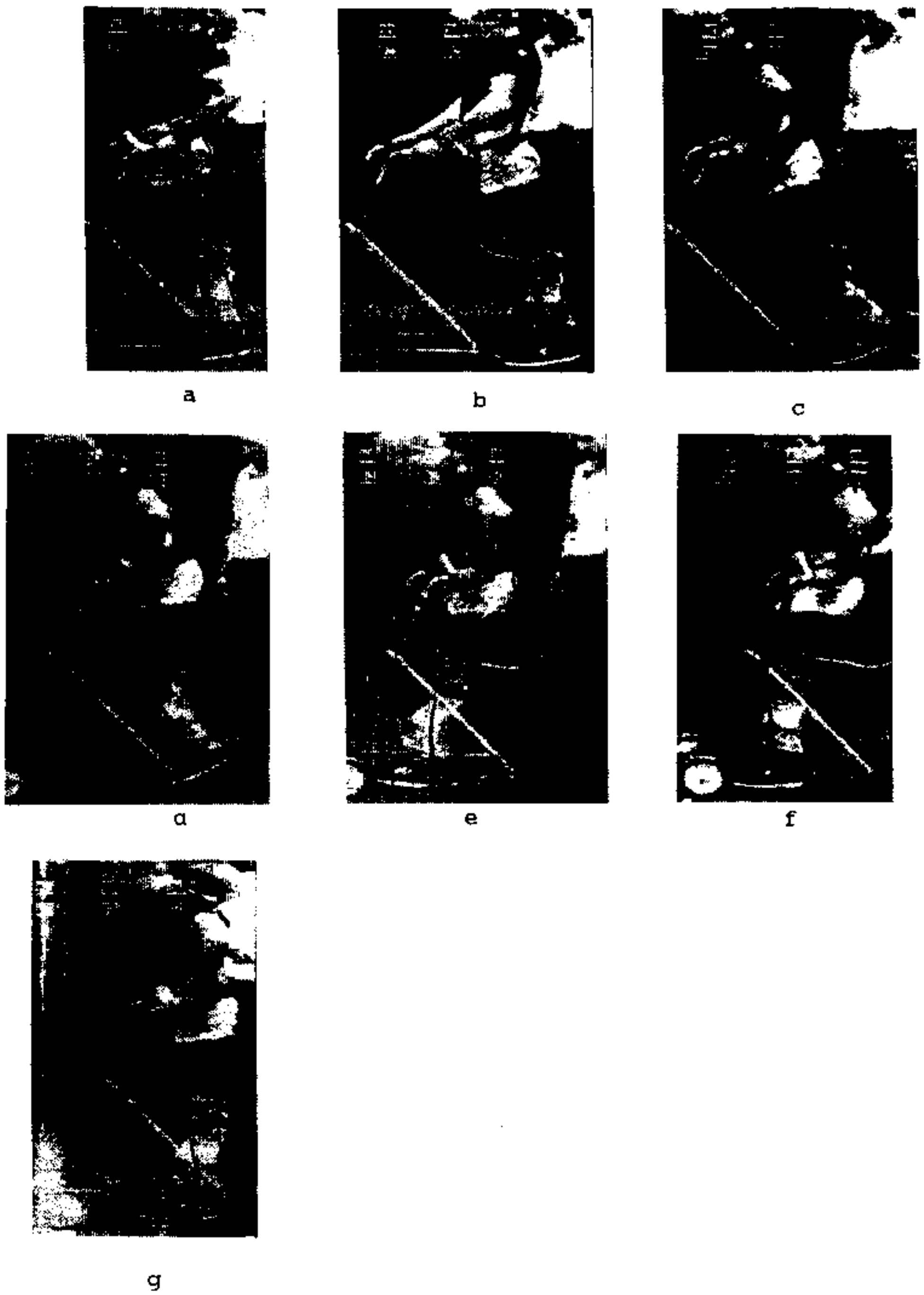


Fig 2. Subject B performing FES swing-through gait. The poor quality of the picture is due to the transition from video.

Fine tuning

The control system can be further tuned for each patient by use of our 'Vicon' motion analysis apparatus and an optimisation package under development at Strathclyde.

Crutches

All the gait at present has been done using a rolator as a walking aid, using crutches will allow greater stride length and their lower mass should give a higher cadence, leading to significant speed increases. We have constructed a mobile overhead support which will prevent the subjects injuring themselves if they should fall in the early stages of training with crutches. We also plan to explore different crutch systems such as saddle crutches [11].

Further trials

All tests so far have been performed in the laboratory, a valid indication of the worth of the gait can only be obtained in a domestic or street environment. An 'intelligent' stand- alone battery-powered stimulator is at present being developed that will allow these more realistic trials.

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REFERENCES

1 Marsolais EB (1986) Stages in the developement of useful FNS- augmented walking. Proc RESNA 9th Ann. Conf., Minneapolis, Minnesota 279-281.

2 Kralj A, Bajd T, Turk T, Krajnik J, Benko H (1983) Gait restoration in paraplegic patients: A feasibility demonstration using multichannel surface electrode FES. J. Rehab R&D. 20:3-20.

3 Cliquet Jr. A (1988) Paraplegic locomotion with neuromuscular electrical stimulation based systems - A feasibility study. PhD thesis, University of Strathclyde, Glasgow.

4 Heller BH, Andrews BJ (1989) An analysis of swinging gaits and their synthesis, Proc of 3rd Vienna International Workshop on Functional Electrostimulation, 77-80.

5 Brindley GS, Polkey MD, Rushton DN (1979) Electrical splinting of the knee in paraplegia, Paraplegia 16:428-435.

6 Phillips GF, Zhang LD, Barnett RW, Mayagoitia R, Andrews BJ (1989) The Strathclyde Research Stimulator for Surface FES. Proc of 3rd Vienna International Workshop on Functional Electrostimulation, 341-342.

7 Andrews BJ, Barnett RW, Phillips GF, Kirkwood CA, Donaldson N, Rushton DN, Perkins DA (1988) Rule-based control of a hybrid orthosis for assisting paraplegic locomotion, Automedica, 11:175-200.

8 Andrews BJ (1986) A short leg hybrid orthosis for assisting locomotion in SCI subjects. 2nd Vienna International Workshop of Functional Electrostimulation. 311-314.

9 Mayagoitia-Hill RE (1990) PhD thesis, Stability in FES and orthoses assisted paraplegic standing, University of Strathclyde, Glasgow.

10 Kirkwood CA, Andrews BJ, Mowforth P (1989) Automatic Induction of Gait Events: a Case Study Using Inductive Learning Techniques. J. Biomed. Eng. 11:511-516.

11 Joll CA (1917) An improved crutch, The Lancet, 1:538.

7 Andrews BJ, Barnett RW, Phillips GF, Kirkwood CA, Donaldson N, Rushton DN, Perkins DA (1988) Rule-based control of a hybrid orthosis for assisting paraplegic locomotion, Automedica, 11:175-200.

8 Andrews BJ (1986) A short leg hybrid orthosis for assisting locomotion in SCI subjects. 2nd Vienna International Workshop of Functional Electrostimulation. 311-314.

9 Mayagoitia-Hill RE (1990) PhD thesis, Stability in FES and orthoses assisted paraplegic standing, University of Strathclyde, Glasgow.

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11 Joll CA (1917) An improved crutch, The Lancet, 1:538.