LONG TERM EFFECTS OF FES-ASSISTED WALKING ON DYNAMIC STIFFNESS OF SPASTIC ANKLE

M.M.Mirbagheri¹,²,³, M.Ladouceur⁴, H.Barbeau⁴, and R.E.Kearney¹

¹Dept. of Biomedical Engineering, McGill University, Canada, ²Dept. of Physical Medicine and Rehabilitation, Northwestern University, USA, ³SMPP, Rehab Institute of Chicago, and ⁴School of Physical and Occupational Therapy, McGill University, Canada

Abstract
The effects of long-term Functional Electrical Stimulation (FES) assisted walking on ankle dynamic stiffness were examined in spinal cord injured (SCI) subjects with incomplete motor function loss. A parallel-cascade system identification method was used to identify intrinsic and reflex contributions to dynamic ankle stiffness at different positions with subjects instructed to remain relaxed. Intrinsic stiffness dynamics were well modeled by a linear second-order model relating intrinsic torque to joint position. Reflex stiffness dynamics were accurately described by a linear, third order model relating half-wave rectified velocity to reflex torque. We examined four SCI subjects before and after long-term use FES-assisted walking (>16 months). Both reflex and intrinsic stiffness decreased in FES subjects following FES-assisted walking, whereas they increased in the control subject. The results suggest that long-term FES-assisted walking may have therapeutic as well as rehabilitation applications, since its use appears to make spastic joint mechanics more normal.

Introduction/Background
Functional Electrical Stimulation (FES) has been used to replace lost descending control and restore a variety of movements, including walking. FES was first developed about 30 years ago as an orthotic system to prevent “foot drop” during hemiplegic walking [1]. Its use in SCI subjects with incomplete motor function was first reported in 1989 [2]. Most spinal cord injuries produce damage above the level of the motoneurons to the lower limb [3]. The lower limb muscles and their motoneurons usually remain functional. The gait of SCI subjects with incomplete lesion is impaired by weaknesses of lower limb muscles [4]. In principle, electrical stimulation of these muscles can alleviate these problems and produce upright, unencumbered walking.

A number of studies have examined the therapeutic effects of long-term FES use. However, since these approaches measure different criteria and are subjective and qualitative in nature, they do not quantify the effects of FES on spasticity.

Recently, we presented a method for distinguishing the relative contributions of intrinsic and reflex mechanisms to overall mechanics. The modulation of reflex stiffness with level of tonic contraction and with ankle position [5] indicated that ankle mechanics are abnormal in SCI subjects and pathological muscle tone is due to enhanced reflex gain and intrinsic stiffness.

The objective of this study was to use this quantitative, objective method to examine the effects of long-term FES-assisted walking on intrinsic and reflex dynamic stiffness in spastic subjects.

Methods
Subjects
Nine SCI subjects (4 females, 5 males) were initially included in this study. Following a four-week initiation program on the proper use of the FES stimulator the participants were asked to use FES-assisted walking as much as possible in their activities of daily living. Only four of them completed the protocol and called FES subjects in this study. They were evaluated before and after using FES-assisted walking for a minimum of 16 months. One SCI subject, who used FES-assisted walking for five months after the initial evaluation, was evaluated 13 months later as a control.

FES-Assisted Walking
The CPN stimulation was provided by one of three stimulators, depending on the required number of channels and availability of the devices. When the subject required stimulations of the quadriceps or stimulation of both CPN the subjects were provided with a Quadstim stimulator (Biomotion Inc.). If the subject needed only one channel of stimulation the subjects were fitted with either a Unistim (Biomotion Inc.) or Mikrofes (Ljubljana) stimulator. Triggering of the CPN stimulation was done by either handswitches or footswitches.

Experimental Protocol
The perturbation amplitude that produced the maximum reflex torque was determined for each subject. A series of pseudorandom binary sequences with this amplitude (varied between 0.025 rad and 0.035 rad) and
a switching-interval of 125ms were applied to perturb the ankle at different angles in the range of motion when subjects remained relax.

Non-Parametric Model
Intrinsic and reflex contributions to the ankle stiffness dynamics were separated using a new parallel-cascade identification method [6] in which:

1. Intrinsic stiffness dynamics were estimated in terms of linear, dynamic impulse response functions (IRF) relating position and torque. This IRF was convolved with the position signal to predict the intrinsic torque, which was subtracted from the observed torque to leave the reflex torque.

2. Reflex stiffness dynamics were estimated by determining the IRF between half-wave rectified velocity and the reflex-torque as the output, using Hammerstein identification methods [6].

Parametric Model
Non-linear least squares methods were used to fit parametric models to the IRFs as follows:

1. The intrinsic compliance dynamics were computed from the intrinsic stiffness IRF and well defined by a linear, second-order high pass system

2. The linear, dynamics of the reflex stiffness were well described by a third order system.

Intrasubject Reliability
Intrasubject reliability was generally high ($r>80$), indicating that the method can be used to track changes in ankle mechanic with time.

Results
Only three of the seven intrinsic and reflex stiffness parameters changed consistently with FES; intrinsic stiffness gain ($K$), viscosity ($B$) and reflex stiffness gain ($G_R$). Figure 1 shows the variation with position of these parameters for one FES subject. All parameters were significantly larger before (pre-FES) than after (post-FES) long-term FES-assisted walking ($p<0.002$). As reported previously, these parameters increased monotonically with dorsiflexion [5].

The percentage changes in parameters were shown to demonstrate the effects of FES-assisted walking. Percentage changes in $K$ and $B$ were obtained by dividing the pre-post difference by the pre-FES value. Figure 3&4 show these changes as a function of position for all five subjects. $K$ decreased at all position for FES subjects by an average of 45%±12% (Figure 2), whereas it decreased by the average of only 8%±16% for the control subject.

Similarly, $B$ decreased by an average of 25%±20% for FES subjects, but increased by 80%±43% in the control subject (Figure 3).
The findings suggest that FES-assisted walking, originally designed to facilitate locomotion, may have therapeutic applications since its use appears to reduce abnormal joint stiffness.

Discussion/Conclusions
This study is the only investigation we are aware of examining the effects of long term FES-assisted walking on intrinsic and reflex dynamic stiffness in spastic subjects. The system identification method used here quantifies joint mechanical properties objectively, and separates the intrinsic and reflex components. The major finding was that both reflex and intrinsic stiffness decreased following FES-assisted walking. The decrease in reflex and intrinsic gain could be due to a variety mechanisms related to FES (CPN stimulation) and/or walking. CPN stimulation could act through reciprocal inhibitory mechanisms by increasing the activity of tibialis anterior muscle. This would not only prevent hypoactivity of this muscle but also decrease hyperactivity of triceps surae muscles. Hence, as found in this study, the intrinsic properties of triceps surae muscle could change because of changes in the activity of these muscles caused by long term FES-assisted walking.

Figure 3: Percentage change in intrinsic viscous parameter ($B$), following FES-assisted walking, as a function of position in all subjects.

Figure 4 shows the percentage change in $G_R$ as a function of position in all subjects. $G_R$ decreased through ROM in the FES subjects by an average of 53%±10%, whereas it increased by 45%±55% for the control subject.

References

Acknowledgment
Supported by a grant from the MRC of Canada and NSERC.