34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

The Effects of Locomotor Training with a Robotic-Gait Orthosis (Lokomat) on Neuromuscular Properties in Persons with Chronic SCI *

Mehdi M. Mirbagheri, *Member, IEEE,* Xun Niu, Matt Kindig, and Deborah Varoqui

Abstract—**We studied the effects of robotic-assisted locomotor (LOKOMAT) training on neuromuscular abnormality associated with spasticity in persons with incomplete Spinal Cord Injury (SCI). LOKOMAT training was performed 3 days/week for 4 weeks, with up to 45 minutes of training per session. Subjects were evaluated before and after 1, 2, and 4 weeks of training, and the effects of training on the intrinsic (muscular) and reflexive components of the neuromuscular properties were quantified over the ankle range-of-motion. A linear (slope&intercept) regression was fit to the stiffness-angle curve. "Growth mixture" modeling was used to identify recovery classes for these parameters over the training period. Two distinct classes were observed. Class 1 subjects had initially higher reflex stiffness parameters (i.e., intercept and slope vs. ankle position) and reduced significantly over the training period. Class 2 subjects initially had lower reflex stiffness parameters and experienced non-significant reductions. Similar results were observed for the intrinsic stiffness intercept; however, intrinsic slope showed no significant improvement over training for either class. These findings demonstrate that LOKOMAT training is effective in reducing reflex and intrinsic stiffness (which abnormally increase in SCI) and improving the abnormal modulation of reflexes over the ankle range-of-motion.**

I. INTRODUCTION

Body weight-supported treadmill training (BWSTT) has been shown to greatly enhance ambulation following spinal cord injury (SCI) [1-5]. In this training, patients are unloaded over a treadmill and manual assistance is provided to simulate walking activity [1-5] — a physically-demanding and time-consuming task that often requires three therapists to perform effectively [1]. Recent advances in technology have prompted the use of robotic devices to assist therapists in the rehabilitation of patients with neurological injury (reviewed in [6]). Colombo and colleagues have developed a driven gait orthosis that operates by a computer interface with a motorized treadmill (LOKOMAT, Fig. 1, [7]). The LOKOMAT provides ambulation assistance similar to BWSTT, but provides swing and stance assistance through a motorized exoskeleton. Actuators at bilateral hip and knee joints allow the LOKOMAT to mimic a physiological gait pattern that will provide the necessary afferent input to improve locomotion.

Recent results have shown that the LOKOMAT training can improve walking capacity by improving gait speed and gait endurance [8, 9]. However, the effects of such training on the abnormal neuromuscular properties that are associated with spastic hypertonia are completely unknown, due to lack of a quantitative objective tool.

Furthermore, typically no intervention has the same impact on all patients. This indicates that the simplified pre- and post-treatment analysis that is customary in the literature fails to track the recovery pattern during treatment, and the use of group-averaging techniques neglects the substantial variation among SCI individuals. Therefore, there is a need for development and use of advanced statistical models, such as growth mixture models, to adequately analyze the therapeutic effects of LOKOMAT on gait impairments and to identify different recovery patterns for these effects.

Accordingly, the first objective of this study was to use the system identification technique to characterize the effects of LOKOMAT on neuromuscular abnormalities associated with spasticity.

The second objective was, for the first time, to use the growth mixture model to identify different recovery patterns for the intrinsic and reflex stiffness measures over the course of the training period. This may help clinicians to identify which patients will benefit most from LOKOMAT training prior to starting the therapy.

II. EXPERIMENTAL PROTOCOL

Twelve spinal cord injury (SCI) subjects with incomplete motor function loss and spasticity at their ankles participated in this study. All the subjects were ambulatory and were able to complete walking impairment evaluations. Each of the subjects participated in tri-weekly LOKOMAT training sessions, and weekly evaluations of their neuromuscular properties using a custom setup.

A. Robotic-Assisted Locomotor (LOKOMAT) Training

The LOKOMAT training is accomplished by four DC motors aligned at the hip and knee joints. Bilateral actuators move the patient's legs through physiological gait patterns over a treadmill whose speed is synchronized with the gait movements. The degree to which the device assists the gait can be adjusted by the therapist. Dynamic body weight support provides automatic lifting and unloading [7].

Subjects were fitted with an overhead harness /counterweight system and unloaded by a counterweight. Subjects were fitted into the LOKOMAT by supporting the trunk and pelvis, aligning the hip and knee joints with the motor axes, and supporting the legs with fitted cuffs (Fig. 1).

---

* This work was supported by grants from the NIH-R01 and the Craig. H. Neilsen Foundation.

M. Mirbagheri is with Northwestern University and the Rehabilitation Institute of Chicago. He can be reached at mehdi@northwestern.edu

D. Varoqui and X. Niu are with Northwestern University and the Rehabilitation Institute of Chicago.

M. Kindig is with the Rehabilitation of Chicago.

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

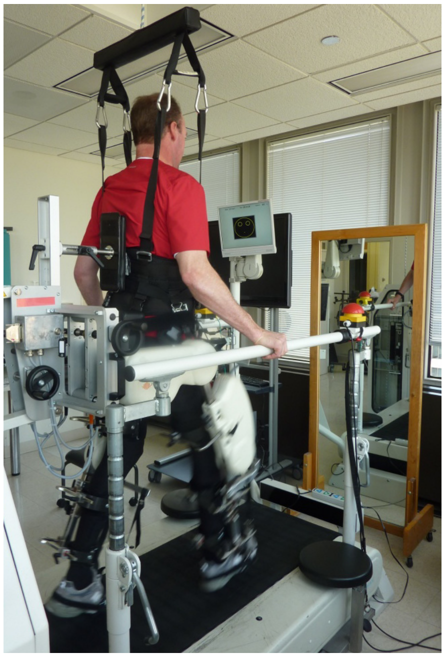

Figure 1: Robotic-assisted Locomotor (LOKOMAT) Training Apparatus

Adjustable elastic restraints attached to the motorized shank supported the foot, maintaining the ankles in the neutral (90°) position.

LOKOMAT training was performed three days per week. Each one-hour session (including set-up time) included up to 45 minutes of training time. Treadmill speed was initially set as low as 1.0 km/h and increased by the therapist up to 2.5 km/h, as tolerated by the subject. Total training time, speed, distance, and the amount of unloading were recorded during each session. Subjects were encouraged to contribute "as much as possible". Training was provided for 4 weeks.

B. Experimental Setup

A custom joint stretching apparatus was used to measure the torque when the subject's ankle was subject to a position perturbation. The device operated as a position control servo, driving the ankle position (flexion/extension) to follow a commanded input. Subjects were seated and secured in an adjustable chair with the ankle strapped to the foot rest and the thigh and trunk strapped to the chair. The seat and foot rest were adjusted to align the ankle axis of the rotation to be coincident with the center of the motor shaft (Fig. 2).

Joint position, velocity and torque were recorded by a potentiometer, tachometer, and torque transducer, respectively. Torque was measured about the center of ankle rotation. Electromyograms (EMGs) placed at the tibialis anterior (TA) and gastrocnemius (GS) were recorded using bipolar surface electrodes. These signals were sampled at 1 kHz by a 16 bit A/D converter, and low-pass filtered at 230 Hz on-line to prevent aliasing.

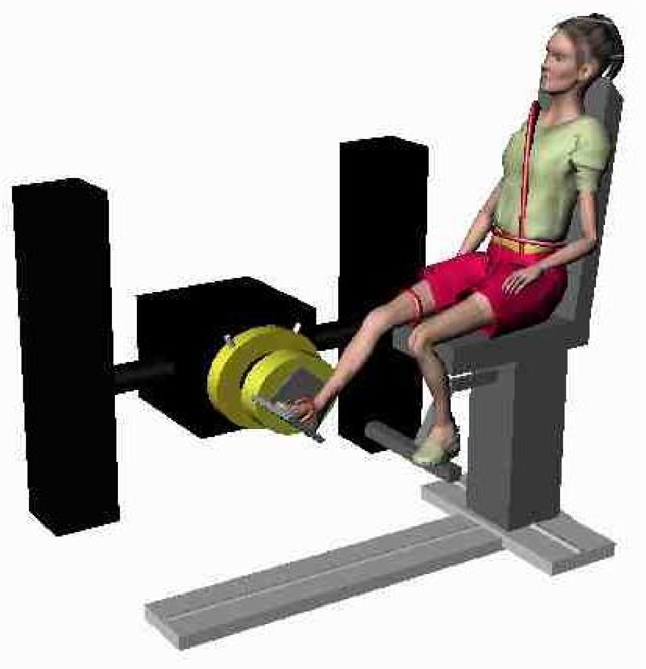

Figure 2: Experimental Setup

C. Operating Conditions

A series of pseudorandom binary sequences with an amplitude of 0.03 rad and a switching-rate of 150ms were used to perturb the ankle at different positions from 30° plantarflexion to 25° dorsiflexon, at 5° increments, while the knee was held at 60° flexion. A 90° angle of the ankle joint was considered to be the neutral position (NP) and defined as zero for this study. These experiments were conducted under the passive condition on the more spastic side. Plantarflexion was considered negative by convention.

Subjects were evaluated four times: at the baseline (i.e. prior to any LOKOMAT therapy), and 1, 2 and 4 weeks after training.

III. ANALYSIS METHODS

A. Parallel-cascade Identification Technique

Intrinsic and reflex contributions to the ankle stiffness dynamics were separated using a parallel-cascade identification technique [10, 11].

Intrinsic stiffness dynamics were estimated by determining the Impulse Response Function (IRF) between position and torque (Fig. 3). A second-order model was fit to the IRF, and the intrinsic stiffness parameter K was calculated. Reflex stiffness dynamics were modeled as a differentiator, in series with a delay, a static nonlinear element and then a dynamic linear element. Reflex stiffness dynamics were estimated by determining the impulse response function between velocity and the reflex-torque, using Hammerstein identification methods. The reflex stiffness G_R was identified from the model. This analysis was performed separately for each of the evaluated ankle positions, yielding stiffness *vs.* angle curves for each subject.

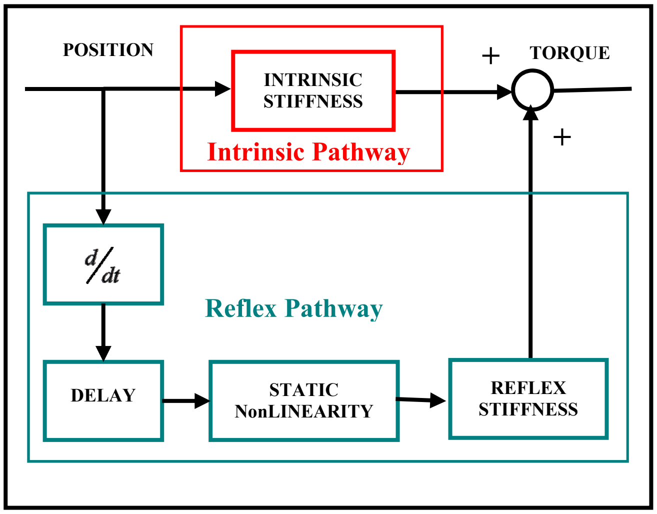

Figure 3: The parallel-cascade system identification model

It was observed that the trend in intrinsic and reflex stiffness with angle was markedly non-linear. In order to produce linear parameters that were amenable to statistical modeling, the square root of the two stiffness values K and G_R was plotted against angle. This resulted in a stiffness-angle trend that had a substantially more linear behavior. In particular, the reflexive stiffness trend could be modeled as a piecewise linear function, consisting of a small slope (i.e. nearly horizontal) function extending from maximum plantarflexion to approximately 25 degrees plantarflexion, then an increasing linear portion extending to approximately 10 degrees of dorsiflexion, and then a decreasing linear function up to maximum dorsiflexion. In this paper, only the slope of the middle portion (the increasing linear function) is presented. For the intrinsic stiffness, a linearly increasing region extending from approximately the angle where the stiffness was minimized to the maximum dorsiflexion angle was defined. Two characteristic parameters were examined for each linear portion: the slope and intercept (i.e. stiffness at neutral position) of the linear regression of the stiffness *vs.* angle trends. The change in these parameters with time was investigated.

B. Growth Mixture Model

Latent class growth (LCG) modeling [12] was applied to identify the progression of stiffness changes with time. This approach finds the inter-subject subpopulation (homogeneous class) by inspecting the intra-subject changes. The observations in each subclass were considered locally independent. The slope and intercept of the intrinsic and reflexive linear fits were compared over time, and each subject was classified into a distinct subclass based on the change in these linear parameters with time [13]. The goodness-of-fit of the classification model was evaluated by the Bayesian information criteria (BIC).

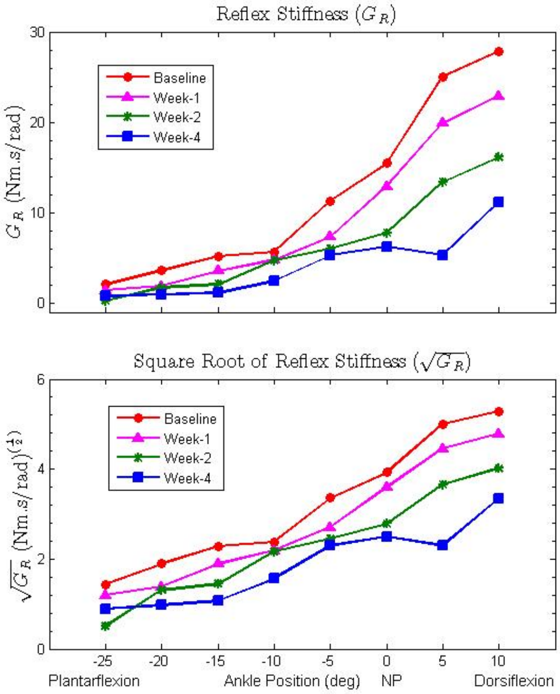

Figure 4: Reflex stiffness (G_R) and its square root vs. position before training (baseline) and after 1, 2, and 4 weeks of training

IV. RESULTS

A. Intrinsic and Reflex Stiffness Parameters

The reflex stiffness G_R vs. ankle position is shown in the top plot of Fig. 4 for a representative subject, at various training weeks. The bottom plot shows the square-root of the same data plotted against ankle position; the linearization of the trends introduced by taking the square root is apparent.

B. The Therapeutic Effects of LOKOMAT Training on Neuromuscular Recovery Patterns

The LCG modeling indicated that two subclasses could be identified, for each of the four linear fit parameters: slope K_{SLP} and intercept K_{INT} for the intrinsic stiffness, and slope G_{SLP} and G_{INT} for the reflex stiffness. In all cases, subjects in Class 1 had a high value of stiffness at baseline, while subjects in Class 2 had a low value of baseline stiffness.

Both reflex slope and intercept decreased for both Classes 1 and 2, with the amount of decrease higher for Class 1 (the high-stiffness group) than for Class 2. This change, however, was significant only for Class 1 ($P < 0.05$), and marginally significant for Class 2 (Fig. 5).

Similar results were found for the intrinsic intercept. However, there were no statistically-significant changes (P=NS) in the intrinsic slope over time for either class. This may be due to substantial inter-subject variability.

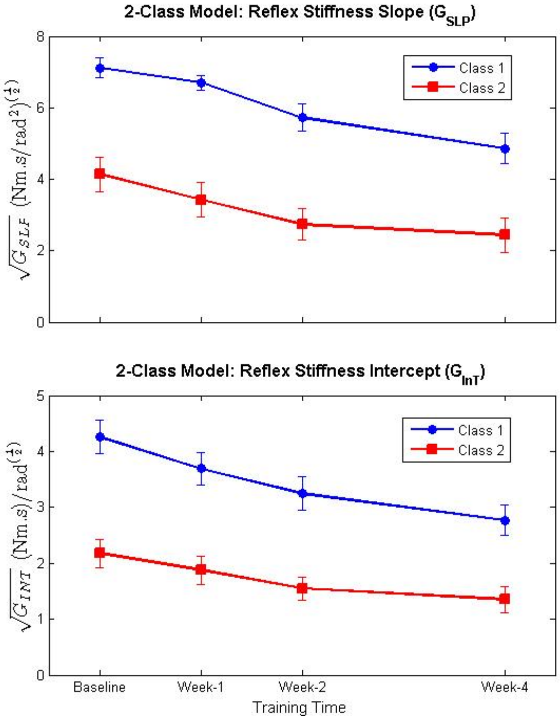

Figure 5: Reflex stiffness parameters before and after 1, 2, and 4 weeks of LOKOMAT training

V. DISCUSSION AND CONCLUSIONS

In this study, the parallel cascade identification technique was successfully used to characterize the effect of LOKOMAT training on ankle stiffness and its reflex and intrinsic components.

Our earlier results indicated that both reflex and intrinsic stiffness increase abnormally after SCI. We used the LCG model to characterize the therapeutic effects of LOKOMAT training on reflex and intrinsic stiffness recovery patterns. The modulation of reflex and intrinsic stiffness with ankle position was characterized by the slope and intercept of the stiffness vs. position curve. Two latent classes were observed for each of the four fit parameters. Patients with a higher reflex stiffness slope (i.e. greater variation with ankle position) and intercept (greater neutral position stiffness), i.e. those subjects in Class 1, showed significant improvements during LOKOMAT training. The reflex stiffness parameters were also reduced in subjects who had lower baseline stiffness but whose rate of changes was lower compared to Class 1. Similarly, the intrinsic intercept decreased significantly due to LOKOMAT training. However, intrinsic slope did not show significant changes. These findings demonstrate that SCI patients with higher neuromuscular abnormality may obtain better improvement from LOKOMAT training.

The lack of significant improvement in patients with a lower stiffness at baseline could be also related to a limited sample size. Further analysis with a larger sample size will clarify this.

Both reflex and intrinsic stiffness, increased abnormally in SCI, were significantly reduced following four weeks of LOKOMAT training. These improvements could be at least partially due to stretching the ankle (from foot drop to the neutral position) during the training, which can modify the ankle neutral position and as a result change its reflexive and intrinsic properties.

These findings demonstrate that LOKOMAT training has the potential to modify the responses of various spinal pathways, which can modify neuromuscular properties and their recovery. Thus, LOKOMAT training can be considered as an effective physical intervention for SCI patients.

REFERENCES

[1] A. L. Behrman and S. J. Harkema, "Locomotor training afer human spinal cord injury: a series of case studies," *Phys Ther,* vol. 80, pp. 688-700, 2000.

[2] H. Barbeau and J. Fung, "The role of rehabilitation in the recovery of walking in the neurological population," *Curr Opin Neurol,* vol. 14, pp. 735-740, 2001.

[3] V. Dietz and S. J. Harkema, "Locomotor activity in spinal cord-injured persons," *J Appl Physiol,* vol. 96, pp. 1954-1960, 2004.

[4] L. Finch, H. Barbeau, and B. Arsenault, "Influence of body weight support on normal human gait: Development of a gait retraining strategy," *Phys Ther,* vol. 71, pp. 842-855, 1991.

[5] A. Werning, M. S., and E. Cagol, "Laufband therapy based on 'rules of spinal locomotion' is effective in spinal cord injured persons," *Eur J Neurosci,* vol. 7, 1995.

[6] B. T. Volpe, H. I. Krebs, and N. Hogan, "Is robot-aided sensorimotor training in stroke rehabilitation a realistic option?," *Curr Opin Neurol,* vol. 14, pp. 745-752, 2001.

[7] G. Colombo, M. Jeerg, R. Schreier, and e. al., "Treadmill training of paraplegic patients using a robotic orthosis," *J Rehabil Res Dev,* vol. 37, pp. 693-700, 2000.

[8] T. G. Hornby, D. H. Zemon, S. Acosta, R. Stine, and W. Z. Rymer, "Changes in locomotor performance in spinal cord injured subjects following body-weight supported, robotic-assisted treadmill training.," *Soc Neuro Abstr.,* 2002.

[9] M. Wirz, D. H. Zemon, R. Rupp, A. Scheel, G. Colombo, V. Dietz, and G. Hornby, "Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial," *Arch Phys Med Rehabil,* vol. 86, pp. 672-680, 2005.

[10] Kearney RE and Hunter IW, "Nonlinear identification of stretch reflex dynamics," *J Ann Biomed Eng,* vol. 16, pp. 79-94, 1988.

[11] Mirbagheri MM, Barbeau H, and Kearney RE, "Intrinsic and reflex contributions to human ankle stiffness: Variation with activation level and position," *Exp Brain Res,* vol. 135, pp. 423-436, 2000.

[12] T. Jung and K. A. S. Wickrama, "An introduction to latent class growth analysis and growth mixture modeling," *Social and Personality Psychology Compass,* vol. 2, pp. 302-317, Jan 2008.

[13] J. A. Hagenaars and A. L. McCutcheon, *Applied latent class analysis*. Cambridge ; New York: Cambridge University Press, 2002.