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Prediction Of Gait Recovery As A Tool To Rationalize Locomotor Training In Spinal Cord Injury

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Abstract— **Our objectives were to explore the effects of robotic-orthosis (LOKOMAT) training on walking impairment recovery in subjects with incomplete spinal cord injury (SCI), and to develop robust predictors of these recovery patterns. Twelve SCI subjects with different degrees of ankle spasticity participated in a 12-session LOKOMAT training regimen. One-hour gait training sessions were provided three times per week for four weeks. Subjects were evaluated at baseline, 1, 2 and 4 weeks after training. The 10-meter and 6-min walking tests and the Time-up-and-Go tests were used to evaluate gait speed and endurance, and functional ambulation and balance. A "growth mixture" model was used to characterize different recovery patterns of these measures. Logistic regression was further used to predict these recovery patterns based on the isometric voluntary contractions (MVC) of ankle flexors and extensors at the baseline. Our results showed that subjects were separable into two different classes of recovery based on severity of their baseline impairments; subjects with a higher walking capacity at the start of training showed significant improvement over four weeks of training. Our findings demonstrated that MVCs were able to predict recovery class membership and can potentially be used as significant predictors for therapeutic functional recovery after SCI.**

Keywords—**robotic, recovery, prediction, impairment, locomotion, gait, voluntary movement, muscle strength, spasticity, ankle, spinal cord injury**

I. Introduction

Body weight supported treadmill training (BWSTT) has been shown to greatly enhance ambulation following 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]). Use of the LOKOMAT is similar to BWSTT but provides swing and stance assistance through a motorized exoskeleton. Actuators at bilateral hip and knee joints programmed by dual personal computers and a current controller allow the LOKOMAT to mimic a physiological gait pattern that will provide the necessary afferent input to improve locomotion.

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 across the entire subject pool neglects the substantial variation among SCI individuals. Therefore, there is a need for the 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, for the first time, to use growth mixture modeling to explore the effects of LOKOMAT training on walking impairment in subjects with incomplete SCI. In particular, we aimed to characterize the recovery patterns of three major validated clinical assessments of gait impairment—*gait speed, gait endurance,* and *functional ambulation and balance*—over a 4-week training period.

The second objective was to develop robust predictors of these recovery patterns, using logistic regression modeling. The outcomes from this study may help clinicians to identify which patients will benefit most from LOKOMAT training prior to being assigned to this intervention. This can reduce unnecessary therapeutic efforts and treatment cost.

II. Experimental Protocol

A. Robotic-Assisted Locomotor (LOKOMAT) Training

The LOKOMAT consists of 4 DC motors aligned at the hip and knee joints of the patient. Bilateral actuators move the patient's legs through physiological gait patterns over a treadmill whose speed is synchronized with the gait movements. The level of gait assistance can be adjusted by the therapist. In addition, dynamic body weight support provides automatic lifting and unloading in real-time [7].

Figure 1: Robotic-assisted locomotor (LOKOMAT) training apparatus (from http://www.hocoma.com/en/products/lokomat/).

Subjects were fitted in the overhead harness /counterweight system and unloaded by a counterweight. Subjects were positioned in the LOKOMAT by supporting the trunk and pelvis, aligning the hip and knee joints at the motor axes, and stabilizing the legs with fitted cuffs (Fig. 1). Foot motion was controlled with adjustable elastic restraints attached from the metatarsal heads and heels to the shank segment of the exoskeleton. These elastic restraints were intended to reduce the incidence of foot drag by nominally holding the ankles in the neutral (90°) position; however, subjects were able (and encouraged) to reproduce the standard plantarflexion/dorsiflexion kinematics of gait as much as possible.

LOKOMAT training was performed three days per week during a one-hour period (including set-up time), with up to 45 minutes of training during a single session. Treadmill speed was started as low as 1.0 km/h and increased 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 four weeks.

B. Experimental Setup

Twelve spinal cord injury (SCI) subjects with incomplete motor function loss and spasticity at their ankles participated in this study. All subjects were aged 42.2±12.6 years (average±standard deviation), and all subjects were tested more than 1 year after their injury (post-stroke time on average 8.9± 9.9 years). No subjects received similar locomotor training in the prior six months, nor were any of the patients taking anti-spastic medication in the 10-day period before and during the training period. All the subjects were ambulatory and were able to complete walking impairment evaluations.

One hour of LOKOMAT training was provided three times a week for four weeks. Subjects were evaluated at four intervals: at the baseline (i.e. prior to any LOKOMAT therapy), and 1, 2 and 4 weeks after training.

Three validated clinical measurements—the 10-meter walking test, the 6-min walking test, and Time-Up-and-Go test—were used to evaluate locomotion. These popular measurements have been widely used as guidelines to evaluate functional walking capacity [8].

The Timed-Up-and-Go (TUG) test was used to evaluate the functional ambulation and balance by measuring the time taken by the subject to stand up from an armed chair, walk 3 meters, and return to a seated position [9].

The 10-meter walking test (10MWT) was used to evaluate walking speed by measuring the time spent to walk 10 meters [10].

The 6-minute walking test (6MWT) was used to assess walking endurance by measuring the distance covered by the subject after 6 minutes of walking.

Isometric maximum voluntary contractions (MVCs) were determined by having subjects contract their ankle muscles maximally in the plantarflexion and dorsiflexion directions while the ankle was held fixed in the neutral position (90°). A torque transducer recorded the plantarflexion (Tp) and dorsiflexion (Td) torque. Subjects were required to hold the desired contraction for at least 5 seconds; MVC was determined as the average value of torque over this interval.

III. Analysis Methods

A. Latent Class Growth Modeling

Latent class growth (LCG) modeling [11] was applied to identify patterns of recovery in subjects’ gait impairment measures. This statistical technique divides the entire sample of subjects into a finite number of groups, denoted as classes [12]. All of the subjects within each class are considered to have the same basic trend with time (in this case, the same recovery pattern); this trend is distinct from that of subjects outside of the class. Within each class, the observations are considered locally independent.

For each subject, the probability that he/she is in a given class was calculated based on maximum likelihood, and the subject was assigned to the class for which they have the highest probability of membership. This technique was used because it was observed that not all subjects exhibited the same recovery pattern, and thus simple group averaging would be misleading. The goodness of fit of the model—i.e., the accuracy of the group classification—was evaluated by the Bayesian information criteria (BIC).

B. Post-Hoc Statistical Analyses

Three post-hoc analyses following the LCG were performed:

(1) For each class, linear regressions between the training week and each of the gait evaluations were performed. The slope (i.e. recovery rate, in s/week or m/week) and intercept (baseline measurement) were evaluated for statistical significance; a significant value of the slope indicated that subjects in that group presented measurable improvements with training.

(2) The initial and final clinical assessments were compared for each class. The Wilcoxon Signed-Rank test was used to determine differences between the pretest and posttest measurements.

(3) Baseline measurements of MVC were inspected by logistic regression [13] to find whether it was a significant predictor for the membership of subjects into the various classes.

A $P<0.05$ was considered significant for all statistical tests.

IV. Results

A. The Effects of LOKOMAT Training on Gait Impairment

Using the growth mixture model, we found two classes of recovery patterns for all of these clinical measures, based on the data collected over four weeks of training (Table 1).

Subjects in class 1 started with a low walking speed (a higher time intercept) while subjects in class 2 started with a higher walking speed (a lower time intercept). The intercept was significantly lower in class 2 than in class 1 for TUG and 10MWT, indicating that subjects in class 2 spent less time to finish both the TUG and 10MWT tests, and had a higher walking capacity at the start of training. The results also revealed that the subjects in class 2 showed significant improvement in TUG and 10MWT over four weeks of LOKOMAT training, as shown in Table 1. No significant progress was observed for subjects in class 1.

Table 1: Recovery classes for three clinical evaluations of functional impairment found by the growth mixture models. Subjects with high walking capacity measured at the baseline (written in red text) improved TUG and 10MWT significantly over a 4-week LOKOMAT training period.

Clinical evaluations	Subclasses	Sample size, %	Growth Model	
			Intercept	Slope
TUG	Class 1	25	51.5 (p=0.035)	1.1 (p=0.496)
	Class 2	75	**16.0 (p<0.001)**	**-0.6 (p=0.032)**
10MW	Class 1	25	60.3 (p=0.005)	-4.3 (p=0.190)
	Class 2	75	**13.8 (p<0.001)**	**-0.6 (p=0.021)**
6MINW	Class 1	25	39.2 (p=0.057)	4.4 (p=0.173)
	Class 2	75	277.0 (p<0.001)	3.1 (p=0.326)

The pretest and posttest comparison revealed that only subjects in class 2 showed significant improvement in their walking speed and in their functional ambulation and balance after 4 weeks of training (Figure 2).

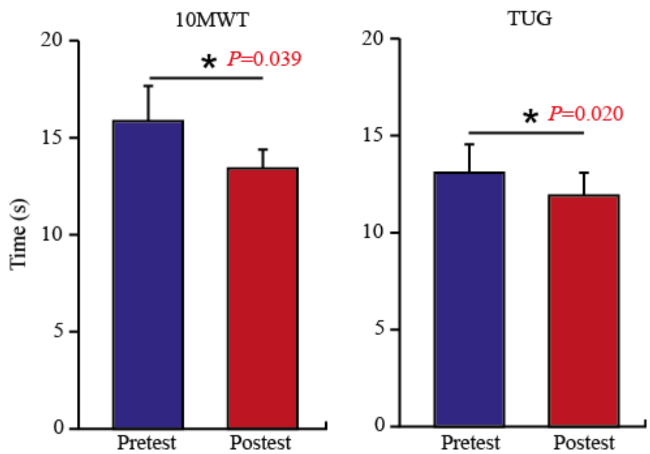

Figure 2: Pretest and posttest comparisons of walking speed (10 MWT) and functional ambulation and balance (TUG) for class 2 (Avg±SD)

B. Prediction of Gait Recovery Patterns using Pretest Kinetic Measures

Logistic regression analysis was used to quantify the effects of baseline Tp (plantarflexor MVC) on class membership. The results showed that Tp was a significant predictor for the classification of subjects into the two classes of clinical measurements of gait impairments. The logistic regression analysis indicated that subjects with a baseline Tp<21 Nm were more likely to belong to class 1, while subjects with a baseline Tp>21 Nm more likely belonged to class 2 (Figure 3).

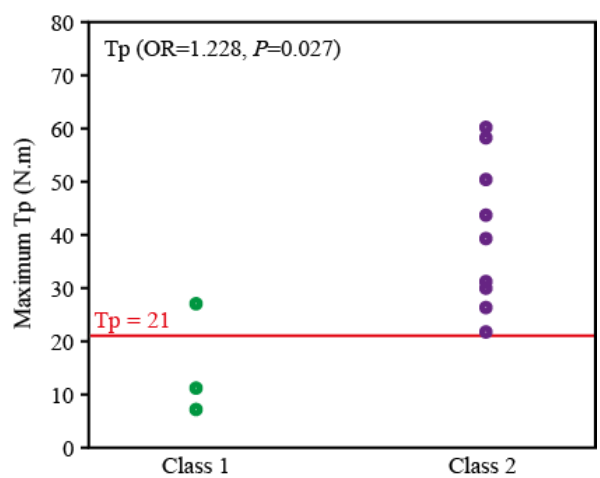

Figure 3: The relationship between Tp measurement at baseline and the membership of the subject, using the logistic regression model.

However, for Td, due to a lack of overlap between classes, there was no need to use modeling. Our data showed that the baseline Td (dorsiflexor MVC) was able to predict the class membership. All subjects in class 1 had a baseline Td<9 Nm while all subjects in class 2 had a baseline Td>9 Nm .

V. Discussion and Conclusions

We used the Latent Class Growth model to characterize the recovery patterns of gait speed, gait endurance, and functional ambulation and balance for SCI subjects who used LOKOMAT intervention. Two classes were observed for all these gait measures. Only patients with a higher walking capacity (class 2) show significant improvements in gait speed and functional ambulation and balance during recovery. The lack of significant gait improvement in patients with a lower walking capacity (class 1) could imply that a more intensive and longer LOKOMAT training regimen may be required for these patients to exhibit a significant improvement.

Our logistic regression results showed that the maximal isometric torque of both ankle dorsiflexors and plantarflexors measured at baseline were able to predict subjects' class memberships based on their walking capacity. This demonstrates that MVCs, a routine clinical measure, can be used as a significant predictor for therapeutic functional recovery after spinal cord injury.

The novel measurement of MVC torque at the ankle joint has the potential to be a fast and reliable clinical assessment tool. It should be noted, however, that the present study included a relatively low number of subjects (12). As a result, these findings should be confirmed on a larger sample size prior to their implementation in the clinic.

These findings suggest that LOKOMAT training has the potential to improve gait impairments for spinal cord injury recovery, and certain patients (those with higher MVC) may experience greater benefit from the LOKOMAT. The outcomes from this study can thus help to optimize treatments for patients with SCI.

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