

Original Article

Research on Design Theory and Compliant Control for Underactuated Lower-extremity Rehabilitation Robotic Systems

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Abstract. [Purpose] The aim of this study was to investigate the immediate effect of Lokomat versus Ergo_bike training using the Probe Reaction Time (P-RT) and 10-m maximum walking speed as the outcome measures, on incomplete spinal cord injury (iSCI) patients. [Subjects] Thirty male T8–L3 level spinal cord injury patients were the subjects. [Methods] The subjects were randomly divided into 2 groups: a Lokomat group and an Ergo_bike group. Each group consisted of 15 subjects. The P-RT and 10 m maximum walking speed were measured before and after the intervention for each group. [Results] The P-RT and the time taken to cover 10 m at maximum walking speed decreased significantly in the Lokomat group. [Conclusion] The Lokomat training not only decreased P-RT, but also improved the walking ability of subjects with iSCI.

Key words: Lokomat, Ergo_bike, Probe reaction time

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INTRODUCTION

After spinal cord injury, the recovery of walking ability is one of the most important milestones in the rehabilitation process and one of the factors with the greatest impact on social and professional reintegration for the patient¹⁾. Patients with iSCI have the potential to regain some ambulatory function. However, ambulation seldom becomes normal and iSCI patients tend to walk slower, depend on walking aids, and are prone to falling²⁾. Underlying causes for this can be spasticity or impairment of balance, strength, or proprioception³⁾. In addition, prolongation of response times might affect walking performance, but has received little attention in the treatment of patients with iSCI.

It is thought that there is a limitation in the capacity of individuals to process information received from the environment. When a movement task is in progress, and another task is concurrently applied, the work required to perform the two tasks at the same time is called a dual task. If the main task is comparatively simple, a comparatively large amount of attention can be allocated to the second task. This makes it possible to perform the second task com-

paratively quickly. Thus, it is interpreted that a lot of attention resources are allocation to the second task. Accordingly, when a second task is demanded during movement task enforcement and the reaction time (RT) for the dual task is relatively short, it is implied that the main task is performed automatically. This study measure is called the probe reaction time⁴⁾. When the main task is walking and the second task is a reaction time test, a shorter P-RT implies better walking performance of subject. A shorter P-RT during walking means less attention is paid to walking. When walking performance is better, less attention is paid to walking. This is explained by the allocatable resources theory. The increase in attention results in extra resources being available and, as long as cognitive effort allocates the resources to the task, there will be better performance of the task⁵⁾. A subject could also pay more attention to prevention of falls. Thus, a shorter P-RT implies better walking performance.

The bicycle ergometer, such as Ergo_bike (Daum Electronics, Germany), has been widely accepted and used in clinical practice. It has been used to improve muscle strength of the lower extremity and cardiorespiratory capacity, but the movement trajectory on a bicycle ergometer differs from walking and the training process is boring. The demand on SCI patients of a bicycle ergometer (muscle strength of the lower extremity; stability of trunk) is high, and it is still unclear whether or not exercise on a bicycle ergometer improves the walking ability of iSCI patients. Thus alternate treatment approaches are desirable.

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Table 1. Subject characteristics

	Lokomat group	Ergo_bike group	Sum total
Age (y)	38.1 ± 7.1	39.2 ± 8.1	38.6 ± 7.6
Height (cm)	170.0 ± 4.1	171.1 ± 4.6	170.6 ± 4.3
Weight (kg)	70.1 ± 3.8	70.7 ± 2.8	70.4 ± 3.3

Values are mean ± SD. No significant differences between groups at the 0.05 alpha level.

In response to the therapeutic challenges presented by bicycle ergometers, robotic devices, such as Lokomat (Hocoma, Inc., Zurich, Switzerland), have recently emerged as a means of automating locomotor training in SCI rehabilitation. Lokomat provides electromechanically assisted locomotion with a constant gait pattern, which is externally paced and controlled by the therapist. It offers some advantages over conventional therapy such as less manpower, longer training sessions, repetitive stepping pattern, kinematic consistency and higher intensity training. It has also been shown to promote the plasticity of locomotor pattern generators at the spinal cord level as well as supraspinal structures^{6, 7}. Nevertheless, despite recent interest in automated locomotor training, there remains very little evidence to support the superiority of this technique over traditional training.

To best determine the key parameters of a large-scale study, preliminary data must first be collected in the form of a pilot study. Therefore, the aim of this study was to investigate the immediate effect of Lokomat versus Ergo_bike training, using the P-RT test and 10-m maximum walking as outcome measures, on the functional recovery of incomplete spinal cord injury patients.

SUBJECTS AND METHODS

Subjects

The subjects were 30 male patients with iSCI (neurological level T8–L3; median time since injury, 189 d) who attended our hospital as inpatients. All subjects gave their consent to participation in this study.

Methods

The subjects were randomly assigned to two groups: a Lokomat group and an Ergo_bike group. Subjects' characteristics are detailed in Table 1. All the subjects were classified using the American Spinal Injury Association Impairment Scale (ASIA) as grade D⁸. The subjects were screened before participating in the study using a medical condition questionnaire. The questionnaire addressed whether or not the subjects could walk independently or with walking aids, or had bone instability (non-consolidated bone fracture, unstable spinal column, or severe osteoporosis). It also addressed whether they had contraindications for Lokomat training: open skin lesion in the lower extremity and torso, severe fixed contractures, circulatory disease, or arthrodesis of the hip, knee or ankle joints. If so, they were excluded from the study.

A physical therapist conducted the clinical examina-

tion, which included measurements of P-RT, the time taken to cover 10 m at maximum walking speed and number of steps; walking velocity, step length and cadence were calculated.

The P-RT of walking was evaluated using MP3 (SN-F110, Signeo), an IC recorder (ICD-UX70, Sony) and headphones. The subjects were asked to respond by saying "Pa" as quickly as possible after hearing an auditory stimulus "Di" stored in the MP3. Both sounds were recorded by the IC recorder. DigionSound5 sound-processing software was used to calculate the intervals between the "Di" and "Pa" sounds. The mean values of the intervals were used as the P-RT. Prior to the experiment, the subjects were given an explanation of the experimental procedure, and they performed trial exercises to familiarize themselves with the procedure. In the actual experiment, the subject was asked to perform the P-RT test while walking at a self-determined speed⁴. The P-RT was measured 10 times consecutively during walking.

To measure the 10 m walking time, lines were drawn at the 2 m and 12 m points on a straight walking track of 14 m, and the time taken walk between the 2 m and 12 m was recorded as the walking time. The 10-m walking time of maximum walking speed was measured 2 times and the mean value was used in the analysis.

The total set-up and treatment time for the Lokomat never exceeded 1 hour. The initial training speed was 1.5 km/h and it was progressively raised to 1.8 km/h as quickly as possible while maintaining gait quality, i.e. symmetrical gait and foot clearance without knee buckling. The body weight system was initiated at 35%, and 70% guidance force was provided for the participants. The subjects were given verbal encouragement to actively step in conjunction with the movement presented by Lokomat.

The Ergo_bike group subjects were instructed to pedal at a pedaling rate of 45 rpm with a work load of 60 W. The height of the saddle was adjusted to the same level as the greater trochanter of subjects. The handlebar was adjusted to keep the shoulder joint flexed at 60° to avoid the influence of trunk movements.

The training time of two groups was 40 minutes. In order to maintain aerobic training, the heart rate was monitored by a therapist and never exceeded 140 beats per minute. The work load could be decreased according to heart rate.

The P-RT and 10-m walking time were measured before and after the intervention for each group.

In order to determine the main effect of the 2 intervention methods, one-way analysis of variance with the Bonferroni correction was used with factors of the P-RT or 10 m

Table 2. Comparison of each measurement item before and after the intervention

	P-RT (ms)	10 m Walking Time (s)
a: Lokomat group-before	309.3 ± 58.7 a<b,d*	18.6 ± 2.3
b: Lokomat group-after	207.9 ± 44.2 b<d*	18.1 ± 2.2
c: Ergo_bike group-before	299.3 ± 51.4 c<d**	18.6 ± 2.3 c>d**
d: Ergo_bike group-after	246.2 ± 47.2	18.1 ± 2.3

*p<0.05, **p<0.01

walking time. The data were analyzed using SPSS Ver. 17.0 for Windows.

RESULTS

The results for each measurement item are shown in Table 2. The P-RT and the 10 m walking time decreased significantly in the Lokomat group. Post-intervention, the Lokomat group had a significantly shorter P-RT than the Ergo_bike group, but there was no difference in the 10 m walking time between the Lokomat group and the Ergo_bike group.

DISCUSSION

This study investigated the immediate effect of exercise using a Lokomat versus Ergo_bike on the P-RT and walking ability of iSCI patients. The Lokomat group showed not only a shortened P-RT, but also improved walking ability.

The P-RT after training was shorter in the Lokomat group. Fast reaction times are essential for maintaining balance when stepping and walking, and Lokomat training might be especially beneficial for ambulating iSCI patients, because they already have locomotor constraints. The study provides new evidence that Lokomat training is more effective than the Ergo_bike training at shortening the P-RT.

Future studies are needed to investigate the change in the ambulatory function after a long period of Lokomat training.

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