INTRODUCTION

Motor learning is driven by error detection and correction. Previous studies with an arm reaching task have shown that the error size may affect the retention of motor learning [1]. Specifically, when healthy subjects practiced adapting to a force perturbation in a reaching task, the aftereffect persisted longer if the perturbation force was applied in a gradual manner (i.e., causing a small size of error) than in an abrupt manner (i.e., causing a large size of error). However, it remains unclear if such motor learning rules can be generalized to leg movement in locomotor training. The purpose of this study was to determine whether the size of error affects the retention of locomotor adaptation in patients with incomplete spinal cord injury (SCI). We hypothesized that a large size of error caused by a large amount of resistance load may be detrimental to the retention of locomotor adaptation.

METHODS

Twelve subjects with incomplete SCI (ASIA D) were recruited for this study. They were asked to walk on a treadmill while a controlled swing phase resistance load was applied to the right leg at the ankle using a customized cable-driven robot [2]. The resistance was applied from the late stance to the mid swing phase of gait.

There were 3 randomized testing conditions: light, medium, and heavy resistance loads. The medium resistance load was determined by the maximum load that each subject could comfortably tolerate. The light and heavy resistance loads were then defined as 30% below and above the medium resistance, respectively. Each test condition consisted of three periods, including baseline (1 minute), adaptation (7 minutes), and post-adaptation (2 minutes). In the baseline period, subjects walked on a treadmill without resistance. In the adaptation period, subjects walked with a controlled resistance load. In the post-adaptation period, the resistance load was unexpectedly released while subjects continued walking on a treadmill.

The ankle trajectory data were recorded using customized position sensors. Electromyographic (EMG) activities of 6 muscles, including the tibialis anterior (TA), medial gastrocnemius (MG), soleus (SO), vastus medialis (VM), rectus femoris (RF), and medial hamstrings (MH) of right leg, were recorded. The stride length of right leg was calculated based on the ankle trajectory data. The EMG data were integrated for the first 30% of swing phase (IEMG data) of gait.

The stride length and IEMG data of each test condition were averaged across the last 20 strides of the baseline period (baseline values). We then calculated the difference between the baseline and the adaptation and post-adaptation values (the first 15 strides of each period). A positive difference indicated an increase in stride length or EMG activity from the baseline. One sample t-test was conducted at the $\alpha$ level of 0.05 to examine if the difference was significantly different from 0.

RESULTS AND DISCUSSION

The stride length from a typical subject during the post-adaptation period is presented in Figure 1A. There was an increase in stride length compared to the baseline, i.e., aftereffect, following the load release, for all three loading conditions. However, the retention of the aftereffect during the post-adaptation period varied depending on the loading condition. Subjects showed the longest retention of aftereffect with the medium resistance load. For instance, the stride length was 6 cm greater than the baseline at the first stride, and remained greater than
the baseline over the first 15 strides during the post-adaptation period. In the heavy resistance condition, the subject had a greater stride length at the first stride (i.e., 8 cm greater than the baseline), but the stride length declined rapidly in the following 9 strides. In the light resistance condition, the subject had a modest increase in stride length at the first stride (3 cm greater than the baseline), and the aftereffect was washed out after the 11th stride.

Statistical analyses using the group data are showed in Figures 1B, C and D. Significant increases in stride length were observed in 10 out of the first 15 strides during the post-adaptation period in the medium resistance condition (Figure 1B). In contrast, significant increases in stride length were observed in only 2 and 3 out of the first 15 strides during the post-adaptation period in the light (Figure 1C) and heavy (Figure 1D) resistance conditions, respectively.

![Figure 1: The gain in stride length in the first 15 strides during the post-adaptation period. (A) A typical subject’s data in all conditions. Data were smoothed using a 3-point moving average technique. (B) Group data in the medium resistance condition. (C) Group data in the light resistance condition. (D) Group data in the heavy resistance condition. *p < 0.05](image)

Subjects experienced a larger error size in stride length when the resistance load was greater during adaptation period. For instance, the average stride length across the first 15 strides during adaptation period was reduced by 0.42 ± 5.8, 0.16 ± 6.2, and 0.1 ± 4.7 cm for the heavy, medium, and light resistance conditions, respectively. In addition, we also observed that the swing time duration during the early adaptation period was increased by 0.032 ± 0.04, 0.025 ± 0.04 and 0.015 ± 0.03 seconds for the heavy, medium, and light resistance conditions, respectively. Meanwhile, the peak velocity of leg swing was reduced by 13.48 ± 23.05, 10.64 ± 16.87 and 5.49 ± 12.79 cm/s for the heavy, medium, and light resistance conditions, respectively.

Due to the larger variability of muscle activity across subjects with incomplete SCI, we did not observe significant changes in the IEMG data during the adaptation and post-adaptation periods for all test conditions.

The size of error during the adaptation period may influence the retention of aftereffect during the post-adaptation period. Specifically, the medium error size in stride length during adaptation was associated with the longest retention of the aftereffect during the post-adaptation period. In contrast, a large error size led to a greater aftereffect during the early post-adaptation period, but declined rapidly. In addition, a small size of error led to a modest amount of aftereffect, and was retained for a short period of time. Thus, it seems that there is an optimal amount of error that is needed to promote a longer retention of motor learning.

CONCLUSIONS

We examined whether the size of error affects the retention of locomotor learning in patients with incomplete SCI. We observed that errors that are too large or too small are detrimental to the retention of motor learning. These results suggest that a patient-specific optimal amount of error in leg kinematics may be needed to enhance the locomotor training in patients with SCI.

REFERENCES


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