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

# Aftereffects of Robotic-Assisted Treadmill Walking on the Locomotor Pattern in Humans*

Kiyotaka Kamibayashi, Hiroaki Kawamoto, and Yoshiyuki Sankai

*Abstract*— **We investigated the possible aftereffects on the locomotor pattern of treadmill walking after walking with the assistance of a robot suit HAL in nine healthy subjects. After walking on a treadmill at a speed of 3.5 km/h for 180 s as a pre-condition, each subject walked with robotic assistance to the hip and knee joints of both legs at the same speed for 600 s. The subjects performed normal walking for 300 s as a post-condition after the assisted walking. Compared with normal walking in the pre-condition, gait cycle duration and step length increased significantly during the assisted walking period. The increased gait cycle duration and step length during the assisted walking period returned to that of the pre-condition period soon after the start of the post-condition. In contrast, the range of motion (ROM) within one step cycle during the initial 60 s of the post-condition period gradually increased in the hip joint, but not in the knee joint. Compared with the mean hip ROM in the initial 10 s of the post-condition, significant increases in mean ROM every 10 s were observed in 4 phases of 20–60 s each in the right leg and in 3 phases of 20–50 s each in the left leg. Although strong aftereffects of the robotic assistance on the locomotor pattern were not observed in the present study, small adaptive changes were seen only in hip ROM during the initial normal walking phase immediately after assisted walking.**

## I. INTRODUCTION

Recent developments in robotic engineering have resulted in robotic devices to provide locomotor training of patients with locomotor disorders and walking assistance for the elderly and individuals with disabilities. Typical gait devices for locomotor training are Lokomat (Hocoma, Volketswil, Switzerland) [1] and Gait Trainer GT I (Reha-Stim, Berlin, Germany) [2]. Clinical studies using these devices have been conducted to clarify the effectiveness of rehabilitation robots in locomotor recovery in patients with stroke or spinal cord injury [3, 4]. As an exoskeletal assistive devices for walking, robot suit HAL (Cyberdyne, Ibaraki, Japan) [5] is well-known.

To date, mechanisms of motor control and motor learning have been also examined using robotic devices [6, 7]. For example, when subjects execute target reaching with a robotic arm that applies a force perturbation to their movement, the reaching movement is initially perturbed by the applied force. Through repetitions of this reaching task, the trajectories of target reaching gradually straighten. After this adaptation to the novel situation, trajectories show mirror-image aftereffects when the force perturbation is unexpectedly removed. The aftereffects that result from the adaptation have been interpreted as evidence that the central nervous system forms a new internal model of body dynamics and force field.

Regarding adaptation during locomotion, studies using a split-belt treadmill with different right and left leg speeds have been extensively conducted by Bastian’s group [8-12]. The subjects needed to adapt to the different speeds of the split-belt where one leg was made to walk faster than the other. The subjects immediately reacted to the speed perturbations by independently scaling their stance and swing times of each leg. When their legs returned to walking at the same speed, this interlimb adaptation induced aftereffects, resulting in walking asymmetry.

Other types of locomotor adaptation have been reported in a condition applying a robotic torque that resists locomotor movement in the hip and knee joints [13]. Locomotor adaptation to the assistive force using a powered ankle-foot orthosis has also been examined [14, 15], but it remains unclear whether aftereffects are observed in normal walking immediately after assisted walking using an exoskeletal robot that provides assistance to the hip and knee joints in the same manner as locomotor rehabilitation. Because less voluntary drive might be required during assisted walking, the step length and range of motion (ROM) in the joints of the lower limb during walking after assisted walking may decrease compared with those before assisted walking. If strong adaptation to the locomotor pattern is induced by robotic-assisted walking, the adaptive changes in the locomotor pattern would pose a fall risk. Therefore, the purpose of this study was to clarify the aftereffects of robotic assistance during walking by examining changes in the locomotor pattern after assisted walking by a robot suit HAL in healthy subjects. For safety reasons, the first pilot study was done in healthy subjects instead of individuals with locomotor impairment.

## II. METHODS

### A. *Subjects*

Nine healthy male subjects with no history of neuromuscular disorders participated in this study. The study

---

*Research supported by “Center for Cybernics Research (CCR)- World Leading Human-Assistive Technology Supporting a Long-Lived and Healthy Society” granted through the “Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST)” initiated by the Council for Science and Technology Policy (CSTP) and the Grant-in-Aid for Young Scientists (B) from the Japan Society for the Promotion of Science.

K. Kamibayashi is with the Faculty of Engineering, Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 3058573 Japan (phone: +81-29-853-5766; fax: +81-29-853-5766; e-mail: kamibayashi@iit.tsukuba.ac.jp).

H. Kawamoto is with the Faculty of Engineering, Information and Systems, University of Tsukuba, Ibaraki 3058573 Japan (e-mail: kawamoto@golem.kz.tsukuba.ac.jp).

Y. Sankai is director of the Center for Cybernics Research (CCR) and professor of the Faculty of Engineering, Information and Systems, University of Tsukuba, Ibaraki 3058573 Japan (e-mail: sankai@golem.kz.tsukuba.ac.jp).

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

was conducted with ethical approval from the local ethics committee. Each subject provided informed consent for the experimental procedures as required by the Declaration of Helsinki.

### *B. Experimental procedure*

A treadmill speed of 3.5 km/h was used for all walking conditions. The subjects were instructed to gaze at a point on a wall and to hold lightly onto the side rails of the treadmill system. Each subject first walked on the treadmill for 180 s as a pre-condition (Fig. 1). After the pre-condition period, the subject wore the robot suit HAL and performed robotic-assisted walking for 600 s (assisted condition). Robotic assistance was continuously applied to the hip and knee joints of both legs during walking. Immediately after the assisted condition, the subject removed the HAL and walked normally on the treadmill for 300 s (post-condition). In all conditions, time measurements were started after a constant treadmill speed of 3.5 km/h was reached.

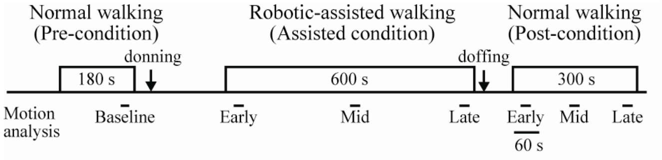

Figure 1. Experimental protocol.

The HAL used in this study is a computer-controlled exoskeletal device. A detailed description of the HAL design and control system can be found elsewhere [5]. In brief, the exoskeletal frame was secured to the subject at the pelvis and at the lower limbs using cuffs. The joints of the HAL frame were aligned to the subject's joints. Direct current motors with harmonic drive systems in the exoskeletal frame generated assistive torque at the hip and knee joints. The amount and timing of the assistive torque provided to each joint for walking were derived from surface electromyogram signals in the flexor and extensor muscles of the hip and knee, as well as from signals of pressure sensors embedded in special shoes worn by the subjects.

### *C. Data measurements*

Five passive reflective markers in each leg attached over the body landmarks on the fifth metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter, and shoulder were used to enable 3-dimensional motion analysis of the lower limb during treadmill walking. The markers were recorded using 4 digital cameras, and the 3-dimensional coordinates of the markers were calculated by a motion analysis system (Frame-DIAS IV, DKH, Tokyo, Japan) using direct linear transformation. The sampling frequency was 60 Hz. The reconstructed coordinate data were smoothed at a cutoff frequency of 6 Hz, using a Butterworth low-pass filter.

### *D. Data analysis and statistics*

Gait cycle, step length, and joint angles of the hip, knee, and ankle were obtained from the coordinate data of the markers to investigate changes in the locomotor pattern. Instances of foot contact and foot off were determined from a trajectory of the fifth metatarsal marker in the sagittal plane. The duration of time from foot contact of the right leg to reoccurrence of the same event with the same leg was computed to determine the gait cycle. The distance between the fifth metatarsal markers of the right and left legs at the instant of foot contact was measured to determine step length, i.e., the step length of the left leg was the distance from the right fifth metatarsal marker to the left fifth metatarsal marker at the instant of left foot contact. The ROM of the 3 joint angles, based on the maximum flexion and extension angles in the sagittal plane throughout a single gait cycle, was calculated to analyze the joint angle during walking. Unfortunately, because the markers on the lateral malleolus, lateral femoral condyle, and greater trochanter were invisible in the present camera setting (2 cameras to 1 leg) because of the HAL's exoskeletal frame, the joint angles could not be obtained in the assisted condition.

In the pre-condition, these parameters were analyzed in 10 gait cycles from 30 s before the end of the measurement as a baseline measurement (Fig. 1). In the assisted condition and post-condition, 10 gait cycles from 15 s after the start of the measurement, 10 gait cycles from the mid-period (assisted condition: 300 s after the start of recording; post-condition: 150 s after the start of recording), and 10 gait cycles from 30 s before the end of the measurement were analyzed as the early, mid, and late phases, respectively (Fig. 1). Furthermore, for detailed analysis, all gait cycles for 60 s from the start of recording in the post-condition were analyzed, and the mean values for each 10-s increment from the start to 60 s were obtained. The mean data of each 10-s increment were normalized to mean values for baseline measurements in the pre-condition.

All data are shown as mean ± SD. One-way repeated measures analysis of variance (ANOVA) was used to evaluate significant differences between the conditions. When the assumption of sphericity by Mauchly's test was violated, Greenhouse-Geisser adjustments were applied to adjust the degrees of freedom. When statistical significance was found by ANOVA, post-hoc multiple comparisons were made using Dunnett's test to identify the significant differences between baseline of the pre-condition and 3 phases of the assisted condition and post-condition. For the data from 60 s in the post-condition, Tukey's post-hoc comparisons were used for the ROM data. The significance level was set at $P < 0.05$.

## III. RESULTS

Fig. 2 shows the mean data for the duration of gait cycle and the step length of each leg in the pre-condition and the 3 phases of the assisted condition and post-condition. The results from one-way ANOVAs showed significant differences for the gait cycle and step length. The post-hoc test showed that the gait cycle in the 3 different phases of the assisted condition was significantly longer than in the pre-condition ($P < 0.001$). In the assisted condition, gait cycle duration in the early phase had already increased to a level similar to that in the mid and late phases. The gait cycle duration in the early phase of the post-condition was shorter than that in the other 2 phases, but a significant difference was not observed between baseline in the pre-condition and the 3 phases of the post-condition. Similarly, the step length in both legs during the assisted condition was significantly longer than that during the pre-condition ($P < 0.001$; Fig. 2). The step length in the assisted condition increased by approximately 0.06 m compared with the pre-condition, whereas that in the post-condition did not differ from that in the pre-condition.

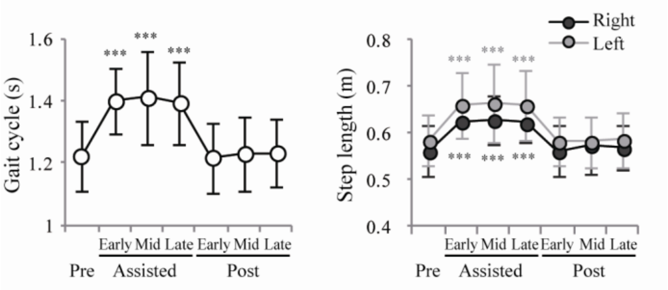

Figure 2. Mean gait cycle and step length of both legs in the pre-condition, assisted condition, and post-condition. *** $P < 0.001$ compared with the baseline data of the pre-condition (black asterisks: right leg, gray asterisks: left leg [right figure]).

Mean ROM measurements in 1 gait cycle at baseline and at the 3 different phases of the post-condition are shown in Fig. 3. Because the reflective markers were hidden by the exoskeletal frame, the joint angles could not be derived during the assisted condition. Among the 3 phases of the post-condition, the hip ROM of both legs tended to be smaller in the early phase than in the other phases, but the difference was not significant. The results of one-way ANOVA for knee and ankle ROM also showed no significant differences.

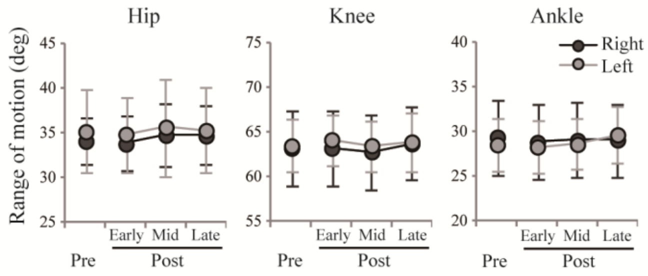

Figure 3. Mean range of motion (ROM) of the hip, knee, and ankle joint angles in the pre-conditon and post-condition.

In detailed analysis of the initial 60 s of the post-condition, some subjects showed gradual changes in hip ROM. Two typical examples of changes in hip and knee ROM for the first 60 s in the post-condition are indicated in Fig. 4. In subject 1 (left panels in Fig. 4), the hip ROM in the right and left legs increased progressively from the start to approximately 40 s. In contrast, the knee ROM remained unchanged for the first minute. In subject 2 (right panels in Fig. 4), the hip ROM was extended for approximately 20 s, but the knee ROM remained unchanged.

Fig. 5 shows the mean hip and knee ROM measurements for the first 60 s of the post-condition in all subjects, which was normalized to mean ROM at baseline in the pre-condition. The values were averaged every 10 s. Significant differences were observed in the 10-s intervals during the initial 60 s for the mean hip ROM in the right and left legs. The right hip ROM in the 4 phases of 20–60 s was significantly greater than that in the initial 10 s. The left hip ROM in the 3 phases of 20–50 s increased significantly compared with that in the initial 10 s. No significant differences in hip ROM were observed between the other phases within the initial 60 s. In contrast, significant changes in knee ROM of both legs were not observed in the initial 60 s of the post-condition. Thus, hip ROM increased gradually in the initial phase of the post-condition, whereas knee ROM remained unchanged.

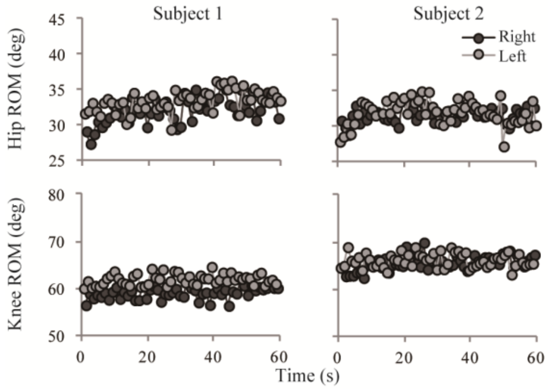

Figure 4. Two examples of changes in hip and knee range of motion (ROM) for the initial 60 s in the post-condition.

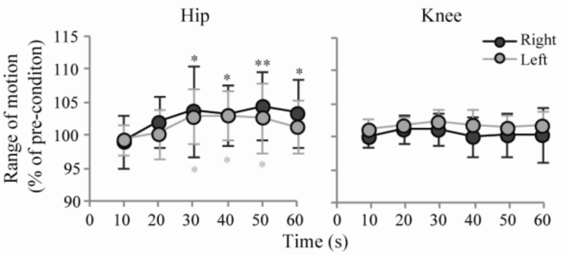

Figure 5. Mean hip and knee range of motion (ROM) of both legs at each 10-s interval within the initial 60 s of the post-condition. ROM was normalized to that at baseline in the pre-condition. * $P < 0.05$, ** $P < 0.01$ compared with the data at the initial 10 s (black asterisks: right leg, gray asterisks: left leg).

## IV. DISCUSSION

In the present study, at the same treadmill speed, the gait cycle duration and step length increased during the robotic-assisted walking using a robot suit HAL compared with non-assisted normal walking. The marker trajectory of the fifth metatarsal in the sagittal plane also differed greatly between walking conditions with and without the HAL. Thus, the locomotor pattern changed markedly because of the robotic assistance. As shown in Fig. 2, no obvious changes in gait cycle duration and step length were observed during assisted walking. Therefore, it appears that changes in the locomotor pattern to a novel walking situation with robotic assistance occurred within a short amount of time. The HAL can provide assistive torque to the hip and knee joints according to electromyographic activities in the lower limb muscles [16]. It is assumed that additional torque due to robotic assistance and biomechanical constraint due to the attachment of the exoskeleton caused the changes in the locomotor pattern.

The hypothesis of the present study was that aftereffects in the locomotor pattern would occur during normal walking performed immediately after robotic-assisted walking because the locomotor pattern and strength of voluntary drive might be changed during the period of assisted walking. However, gait cycle duration and step length, even in the early phase of the post-condition after assisted walking, were not significantly different from those at baseline (Fig. 2). Moreover, the mean ROM in the early post-condition phase did not differ from that at baseline (Fig. 3). Thus, it seems that the aftereffects were not observed in these parameters within 10 gait cycles from 15 s after the start of the post-condition. Compared with the previous studies using a split-belt treadmill that showed clear aftereffects in locomotor pattern [8, 10], the subjects in the present study did not appear to need strong voluntary coordination to adapt to the novel locomotor condition because the robotic torque was assisting each joint during walking. In addition, the subjects could recognize no robotic assistance in the post-condition owing to the removal of the HAL. These factors might limit the occurrence of aftereffects from assisted walking.

However, the hip ROM tended to gradually increase during the initial 60 s of the post-condition (Figs. 4 and 5). Because the time was started after a constant treadmill speed was attained, the ROM changes were not caused by gradual increases in treadmill speed. The hip flexion torque during the swing phase and the hip extension torque during the stance phase by HAL could have been associated with the changes in hip ROM during the initial post-condition phase. The subjects seemed to gradually de-adapt to the effects of the robotic assistance by detecting the resulting error, the difference between the predicted movement outcome and the observed movement outcome. This type of error learning of an internal model is thought to occur in the cerebellum [17, 18]. Indeed, damage to the cerebellum has been reported to impair the adaptation process by decreasing trial-by-trial improvements during adaptation to a new demand and diminishing the stored aftereffect upon demand removal [9]. In contrast to the hip ROM, the knee ROM in the post-condition remained unchanged for 60 s. The aftereffects in the present study were specific to the hip joint. This observation may mean that the modification of the voluntary drive in response to the robotic assistance was concerned with the hip joint rather than the knee joint.

In the present study, clear aftereffects during walking performed after assisted walking did not occur in all subjects. However, given that small adaptive changes in hip ROM were observed in the initial post-condition phase, stronger adaptation might be induced by longer assistance duration and greater assistive torque. Moreover, it is possible that the extent of the effects due to robotic assistance in the elderly and individuals with disabilities may differ from that in healthy individuals. Therefore, further study is needed to clarify the aftereffects due to assistance from a rehabilitation robot. Quantitative assessment of the extent to which voluntary force production decreases during assisted walking by measuring muscle activity in the lower limb also appears necessary. In addition, the changes in the joint angles of the lower limb should be investigated during assisted walking. To better assist with locomotion, it is imperative to determine how humans respond to mechanical assistance from a robotic device. It is hoped that accumulating research results concerning locomotor adaptation from robotic devices will lead to the development of safer robotic devices and more effective locomotor training programs.

## REFERENCES

[1] G. Colombo, M. Joerg, R. Schreier, and V. Dietz, “Treadmill training of paraplegic patients using a robotic orthosis,” *J. Rehabil. Res. Dev.*, vol. 37, pp. 693-700, 2000

[2] S. Hesse, A. Waldner, and C. Tomelleri, “Innovative gait robot for the repetitive practice of floor walking and stair climbing up and down in stroke patients,” *J. Neuroeng. Rehabil.*, vol. 7, pp. 30, 2010

[3] M. Wirz, D. H. Zemon, R. Rupp, A. Scheel, G. Colombo, V. Dietz, and T. 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

[4] M. Pohl, C. Werner, M. Holzgraefe, G. Kroczek, J. Mehrholz, I. Wingendorf, G. Hoolig, R. Koch, and S. Hesse, “Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS),” *Clin. Rehabil.*, vol. 21, pp. 17-27, 2007

[5] H. Kawamoto, and Y. Sankai, “Power assist method based on Phase Sequence and muscle force condition for HAL,” *Adv. Robotics*, vol. 19, pp. 717-734, 2005

[6] T. Brashers-Krug, R. Shadmehr, and E. Bizzi, “Consolidation in human motor memory,” *Nature*, vol. 382, pp. 252-255, 1996

[7] D. J. Reinkensmeyer, J. L. Emken, and S. C. Cramer, “Robotics, motor learning, and neurologic recovery,” *Annu. Rev. Biomed. Eng.*, vol. 6, pp. 497-525, 2004

[8] D. S. Reisman, H. J. Block, and A. J. Bastian, “Interlimb coordination during locomotion: what can be adapted and stored?,” *J. Neurophysiol.*, vol. 94, pp. 2403-15, 2005

[9] S. M. Morton, and A. J. Bastian, “Cerebellar contributions to locomotor adaptations during splitbelt treadmill walking,” *J. Neurosci.*, vol. 26, pp. 9107-9116, 2006

[10] J. T. Choi, and A. J. Bastian, “Adaptation reveals independent control networks for human walking,” *Nat. Neurosci.*, vol. 10, pp. 1055-1062, 2007

[11] D. S. Reisman, R. Wityk, K. Silver, and A. J. Bastian, “Locomotor adaptation on a split-belt treadmill can improve walking symmetry post-stroke,” *Brain*, vol. 130, pp. 1861-1872, 2007

[12] A. J. Bastian, “Understanding sensorimotor adaptation and learning for rehabilitation,” *Curr. Opin. Neurol.*, vol. 21, pp. 628-633, 2008

[13] T. Lam, M. Anderschitz, and V. Dietz, “Contribution of feedback and feedforward strategies to locomotor adaptations,” *J. Neurophysiol.*, vol. 95, pp. 766-773, 2006

[14] S. M. Cain, K. E. Gordon, and D. P. Ferris, “Locomotor adaptation to a powered ankle-foot orthosis depends on control method,” *J. Neuroeng. Rehabil.*, vol. 4, pp. 48, 2007

[15] K. E. Gordon, and D. P. Ferris, “Learning to walk with a robotic ankle exoskeleton,” *J. Biomech.*, vol. 40, pp. 2636-2644, 2007

[16] H. Kawamoto, S. Taal, H. Niniss, T. Hayashi, K. Kamibayashi, K. Eguchi, and Y. Sankai, “Voluntary motion support control of Robot Suit HAL triggered by bioelectrical signal for hemiplegia,” *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, vol. 2010, pp. 462-6, 2010

[17] K. Doya, “Complementary roles of basal ganglia and cerebellum in learning and motor control,” *Curr. Opin. Neurobiol.*, vol. 10, pp. 732-9, 2000

[18] J. Doyon, and H. Benali, “Reorganization and plasticity in the adult brain during learning of motor skills,” *Curr. Opin. Neurobiol.*, vol. 15, pp. 161-167, 2005