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Original Article

Development and verification of a cane for treadmill gait training

Hiroki Tanikawa, RPT, DMSc,[1] Satoshi Hirano, MD, DMSc,[2] Shigeo Tanabe, RPT, PhD,[1] Ikuko Fuse, MD,[2] Kei Ohtsuka, RPT, DMSc,[1] Masahiko Mukaino, MD, DMSc,[2] Ieyasu Watanabe, RPT,[3] Daisuke Katoh, RPT,[3] Akihito Uno, PO,[4] Hitoshi Kagaya, MD, DMSc,[2] Eiichi Saitoh, MD, DMSc[2]

[1]Faculty of Rehabilitation, School of Health Sciences, Fujita Health University, Toyoake, Aichi, Japan
[2]Department of Rehabilitation Medicine I, School of Medicine, Fujita Health University, Toyoake, Aichi, Japan
[3]Department of Rehabilitation, Fujita Health University Hospital, Toyoake, Aichi, Japan
[4]Orthopedic Services Division, Tomei Brace Co., Ltd., Seto, Aichi, Japan

ABSTRACT
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Objective: To clarify the influence of using a handrail during treadmill gait and to verify the effectiveness of a gait training cane developed in this study.

Methods: A cane for treadmill gait training was developed by fixing to a steel base a multipoint cane having a structure that moves back and forth and right and left. Five hemiplegic patients were required to walk on a treadmill without using the handrail, with using the developed cane, and with using the handrail, and their gait was compared using a three-dimensional motion analysis system.

Results: Both the step length and affected-side single-stance phase duration were significantly longer in the gait without the handrail compared to that with the developed cane and with the handrail. No significant differences were observed in the quantitative degree of abnormal gait patterns, but there was a tendency to increase in the same order.

Conclusions: Using a handrail assists the affected-side lower-limb stance and swing and might make it easier to employ compensatory movements. This study shows that using the developed cane during treadmill gait could be a possible training task, in which the difficulty level is between gait training with a handrail and without a handrail.

Key words: hemiplegia, treadmill, handrail, cane, motor learning

Correspondence: Hiroki Tanikawa, RPT, DMSc
Faculty of Rehabilitation, School of Health Sciences, Fujita Health University, 1−98 Dengakugakubo, Kutsukake, Toyoake, Aichi 470−1192, Japan.
E-mail: tanikawa@fujita-hu.ac.jp

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Introduction

Most stroke patients exhibit gait disturbance. An important goal for these patients is to be able to walk independently as this is one of the deciding factors on whether or not they can be discharged to their home [1]. A cane, which is an assistive device encouraging independent walking, is continuously used not only during gait training but also after discharge. In addition to increasing the support base and stabilizing the standing balance, using a cane increases the affected-side step length and improves the gait velocity by assisting in shifting the weight to the unaffected side and pushing off the affected side [2]. As task-oriented physical therapy, treadmill gait training is performed. Improvements in gait velocity and step length in patients with stroke in the early phase after onset have been reported [3]. One of the advantages of treadmill gait training is the ability to control the difficulty level by adjusting the treadmill belt speed, for more efficient gait training [4]. Moreover, the standard treadmill has a handrail, and its use during treadmill gait stabilizes the dynamic postural balance and reduces lower-limb muscle activity and energy consumption [5−7]. Thus, the application to patients with poor gait ability is another advantage of treadmill gait training [8, 9]. In contrast, excessive dependence on the handrail during treadmill gait encourages learning excessive compensatory movements [7]. Because the handrail is a more stable support structure than a cane, it makes it

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easier to shift the weight to the unaffected side and push off the affected limb. In fact, one study reported a greater reduction in energy consumption when using a handrail during treadmill training compared to using a cane during overground gait training [6]. Therefore, excessive dependence on the handrail encourages learning excessive compensatory movements, and continuous dependent use of a handrail might not directly lead to attaining and improving independent overground gait with a cane. Thus, if it were possible to provide treadmill gait training without excessive dependence on the handrail, it could more efficiently achieve independent overground gait with a cane. In a pilot study, the use of a typical T-cane during treadmill gait required the additional task of repositioning the cane because it was lifted up. The operation of a cane during treadmill gait would be a more difficult task than overground gait with a cane, so a cane for treadmill gait training was developed. The purpose of the present study was to clarify the influence of using a handrail during treadmill gait and to investigate the effectiveness of the developed cane for treadmill gait training in hemiplegic patients.

Methods

1. Development of a cane for treadmill gait training

A multipoint cane (New Four-Point Walking Stick, TS402; Fuji Home Co., Ltd., Tokyo) having a structure that moves back and forth and right and left at a maximum angle of 10° was fixed to a steel base (SS400; 200×120×18 mm) covered with ethylene vinyl acetate (EVA) resin (Figure 1-A). Two bolts (M5×20; 5 mm in diameter, 20 mm in length) were used to fix the structure, and urethane rubber (5 mm) was attached to the bottom face for vibration isolation and slip prevention (Figure 1-B, C). The total weight of the cane was 4.2 kg.

2. Verification of the effectiveness of the developed cane

2.1 Subjects

Five hemiplegic patients (four men, one woman) were enrolled in this study. The inclusion criteria were hemiplegia due to the first occurrence of brain disease, ability to walk without an orthosis, ability to walk without a cane although the patient can walk independently with a cane in daily life, and informed consent for participation in this study. The exclusion

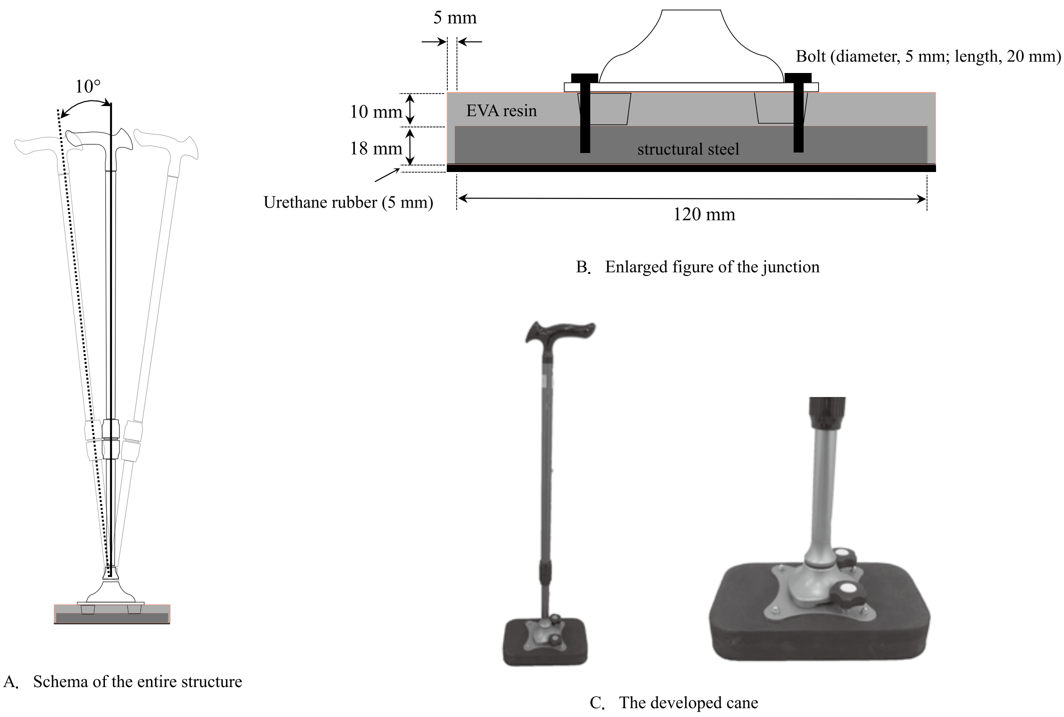

Figure 1. Developed cane for treadmill gait training.
A. Schema of the entire structure.
The structure of the cane is movable with a maximum angle of 10° in every direction using a ball joint as the rotation center between the structure and the base.
B. Enlarged figure of the junction.
Enlarged figure of the junction between the cane and the steel base viewed from the front.
EVA, ethylene vinyl acetate.
C. The developed cane.

criteria were progressive neurological disease, lower limb orthopedic disease, severe joint contracture, and joint deformity. Among the five patients, three had a cerebral hemorrhage, one had a cerebral infarction, and one had a brain abscess. Three patients had right hemiplegia and two patients had left hemiplegia. The mean age was 46 years (range, 18–74 years) with a mean height of 168.6 cm (range, 161.0–176.0 cm) and mean weight of 61.0 kg (range, 51.0–76.0 kg). The mean time from onset was 808 days (range, 51–1,843 days). All patients used a T-cane.

2.2 Procedure

The subjects' comfortable overground gait velocity was measured. They were required to walk on a 12-m long walkway, and the mean velocity of walking the 10-m center of the walkway was obtained using a stopwatch for two trials. Measurement conditions, obtained in random order, were as follows: with a cane that they normally use and without a cane.

Colored markers (30 mm in diameter) were placed bilaterally on the acromion, iliac crest, hip joint (one-third of the distance from the great trochanter on a line joining the anterior superior iliac spine and great trochanter), knee joint (midpoint of the anteroposterior diameter of the femoral epicondyle), ankle joint (lateral malleolus), and head of the fifth metatarsal. Subjects were then instructed to walk on the treadmill (ADAL 3D; Tecmachine, Andrézieux-Bouthéon, France). The treadmill belt speed was set at a comfortable overground gait velocity without a cane. The measurement conditions were 1) without using the handrail; 2) with the developed cane for treadmill gait training, used by the unaffected upper limb; and 3) with the handrail attached to the treadmill, used by the unaffected upper limb. The cane and handrail in conditions 2 and 3 were set at the same height and position as normally used for the cane. In condition 2, the subjects were instructed not to lift and move the cane. The height from the ground to the ball joint of the cane was 7.0 cm. Moreover, in condition 3, the subjects were instructed not to tightly grip the handrail. At least 30 s after the start of walking on the treadmill and stabilization of the gait, the gait was recorded under the three conditions in random order using a three-dimensional motion analysis system (KinemaTracer®; KISSEI COMTEC, Matsumoto, Japan) with a sampling frequency of 60 Hz for 20 s. Sufficient rest was provided between trials.

To verify the validity at the treadmill belt speed, the subjects' comfortable overground gait velocity with a cane was compared to that without a cane. Moreover, the influence of the developed cane on the gait was quantitatively investigated by comparing temporal and spatial factors and index values indicating the degree of knee extensor thrust, retropulsion of the hip, circumduction, and hip hiking under each gait condition [8–11]. The definitions of four abnormal gait patterns are shown in Table 1, and the calculations for index values showing the degree of each abnormal gait pattern are presented in Table 2. Statistical analyses were conducted using JMP 13 software (SAS Institute Inc., Cary, NC USA). The paired *t*-test was used to compare the comfortable overground gait velocity and two-way analysis of variance followed by paired *t*-test with Bonferroni correction was used to compare gait parameters obtained from the three-dimensional treadmill gait analysis. *p*-Values < 0.05 were considered statistically significant.

Results

The comfortable overground gait velocity was 2.0 ± 0.6 km/h without a cane and 1.9 ± 0.6 km/h with a cane (mean ± SD), with no significant difference between them ($p = 0.21$).

Temporal and spatial factors obtained from the treadmill gait analysis are shown in Figures 2 and 3, and index values quantitatively showing the degree of abnormal gait patterns are presented in Figure 4. Analysis of variance showed significant differences in the unaffected-side step length ($p = 0.02$), affected-side swing phase duration ($p = 0.03$), and affected-side

Table 1. Definition of abnormal gait patterns [8–11].

Abnormal gait pattern	Definition
Knee extensor thrust	A dynamic, rapid knee extension during the loading response to a terminal stance on the affected leg
Retropulsion of the hip	The affected hip joint does not continually move forward over the affected ankle joint during the loading response to mid-stance
Circumduction	The lower extremity of the affected side shows hip joint abduction and lateral rotation during initial swing to mid-swing and hip joint adduction and medial rotation during mid-swing to terminal swing, following a semicircular trajectory
Hip hiking	The pelvis on the affected side is raised during pre-swing to mid-swing, associated with shortening of the trunk on the affected side

Table 2. Calculation of index values for abnormal gait patterns [8-11].

Abnormal gait pattern	Calculation for index values
Knee extensor thrust	The difference between the maximum *Y*-coordinate velocity of the knee in the single-stance phase and treadmill gait speed
Retropulsion of the hip	The average distance between the *Y*-coordinate of the ankle joint and the *Y*-coordinate of the toe in the swing phase, corrected by the lower limb length*
Circumduction	The difference in distance between the lateral-most *X*-coordinate of the ankle joint marker in 25-75% of the swing phase and the medial-most *X*-coordinate in 25-75% of the stance phase, corrected by the lower limb length*
Hip hiking	The difference between the maximum values of the *Z*-coordinate of the hip joint marker during the swing phase and the *Z*-coordinate of the contralateral hip joint marker simultaneously, corrected by the mean left-right difference of the *Z*-coordinate during the double support phase

X, *Y*, and *Z* coordinates indicate lateromedial, anteroposterior, and vertical directions, respectively.
*Corrected by the lower limb length: the index value is expressed as a percent of the *Z*-coordinate of the hip joint in a quiet standing position.

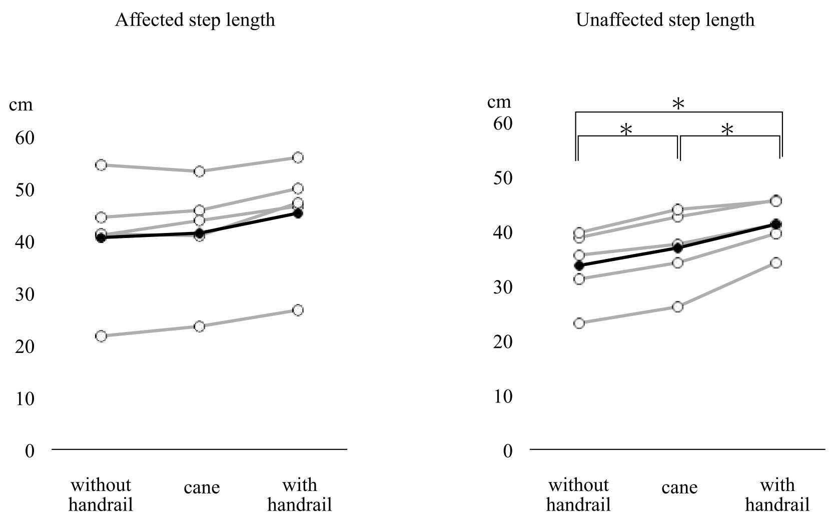

Figure 2. Spatial factors obtained from three-dimensional treadmill gait analysis.
Step length under each condition is shown. The horizontal axis indicates conditions, and the vertical axis indicates step length (cm). Open circles represent the data on subjects, and closed circles represent the mean of all subjects.
*$p < 0.05$, paired *t*-test with Bonferroni correction.

single-stance phase duration ($p < 0.01$). Unaffected-side step length was 33.7 ± 6.8, 36.9 ± 7.2, and 41.2 ± 4.7 cm (mean ± SD) under condition 1 (without a handrail), condition 2 (with the developed cane), and condition 3 (with a handrail), respectively, with significant differences in all pairs of conditions (between conditions 1 and 2, $p < 0.01$; conditions 1 and 3, $p < 0.01$; and conditions 2 and 3, $p = 0.03$). In the same manner, the affected-side step length was 40.6 ± 11.9, 41.5 ± 11.0, and 45.3 ± 11.0 cm (mean ± SD), respectively, with no significant difference ($p = 0.74$). However, there was an increasing tendency in the order of condition 1, 2, and 3 (Figure 2).

The affected-side swing phase duration was 0.46 ± 0.06, 0.47 ± 0.04, and 0.55 ± 0.03 s (mean ± SD) under conditions 1, 2, and 3, respectively, with a significant difference between conditions 2 (with the developed cane) and 3 (with a handrail) ($p = 0.03$; between conditions 1 and 2, $p = 1.00$; conditions 1 and 3, $p = 0.09$) (Figure 3). In the same manner, the affected-side single-stance phase duration was 0.32 ± 0.02, 0.37 ± 0.03, and 0.45 ± 0.05 s (mean ± SD) under conditions 1, 2, and 3, respectively, with significant differences in all pairs of conditions (between conditions 1 and 2, $p = 0.03$; conditions 1 and 3, $p = 0.04$; and conditions 2 and 3, $p = 0.03$) (Figure 3). The double-stance phase

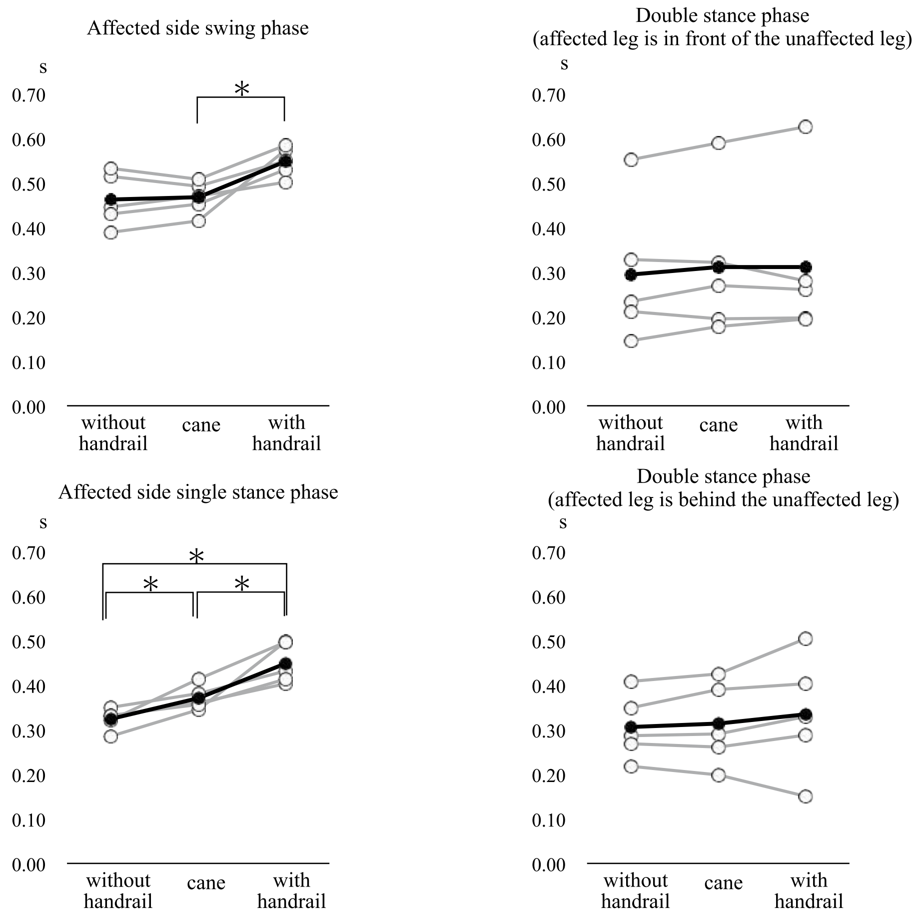

Figure 3. Temporal factors obtained from three-dimensional treadmill gait analysis. The real time for each phase in a gait cycle under each condition is shown. The horizontal axis indicates conditions, and the vertical axis indicates time (s). Open circles represent the data on subjects and closed circles represent the mean of all subjects.
*$p < 0.05$, paired t-test with Bonferroni correction.

duration in which the affected leg is behind the unaffected leg was 0.29 ± 0.16, 0.31 ± 0.17, and 0.31 ± 0.18 s (mean ± SD), and the double-stance phase duration in which the affected leg is in front of the unaffected leg was 0.31 ± 0.07, 0.31 ± 0.09, and 0.33±0.13 s (mean ± SD) under conditions 1, 2, and 3, respectively, with no significant differences (p = 0.91 and 0.71, respectively) (Figure 3).

The index values were 0.3 ± 0.6, 0.2 ± 0.5, and 0.0 ± 0.5 km/h for knee extensor thrust and −4.9 ± 4.9, −6.3 ± 2.3, and −6.9 ± 3.0% (mean ± SD) for retropulsion of the hip under conditions 1, 2, and 3, respectively, with no significant differences (p = 0.64 and 0.65, respectively). However, there was a decreasing tendency in the order of condition 1 (without a handrail), 2 (with the developed cane), and 3 (with a handrail) (Figure 4). The index values were 8.8 ± 3.7, 9.6 ± 4.6, and 10.4 ± 4.7% for circumduction and 7.4 ± 4.9, 6.9 ± 4.3, and 8.1 ± 4.5% (mean ± SD) for hip hiking under conditions 1, 2, and 3, respectively, with no significant differences (p = 0.86 and 0.93, respectively). However, the index values for circumduction tended to increase in the order of condition 1 (without a handrail), 2 (with the developed cane), and 3 (with a handrail), and the index value for hip hiking under condition 3 was the largest (Figure 4).

Discussion

In this study, we developed a cane for treadmill gait training and investigated its effectiveness for a gait training task with the difficulty level between treadmill gait with and without the use of a handrail, aiming to avoid learning excessive compensatory movements during gait and improve overground gait ability with a cane.

Comparing treadmill gait with and without a handrail, the affected-side single-stance phase and swing phase duration, and the unaffected-side step length in gait with a handrail were significantly longer than that without a handrail. The affected-side step length also tended to increase in gait with a handrail. These results were similar to those of a previous study [12] that examined the effectiveness of a cane on overground gait. The benefits of using a cane and a handrail were to not only increase the support base and

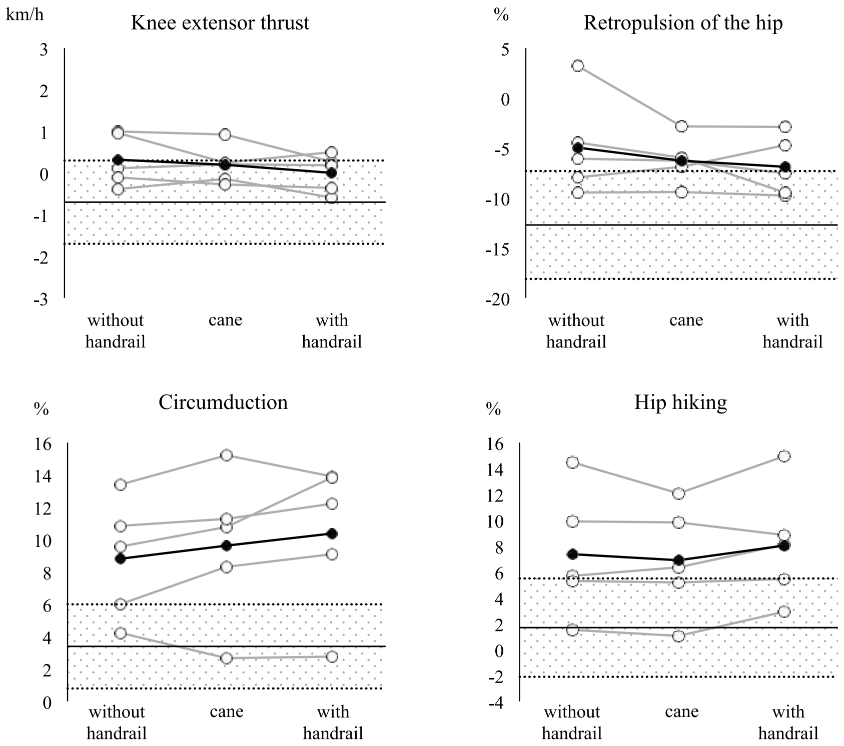

Figure 4. Degree of abnormal gait patterns obtained from three-dimensional treadmill gait analysis.
The degree of abnormal gait patterns under each condition is shown. Open circles represent the data on subjects and closed circles represent the mean of all subjects. As a reference, horizontal solid lines indicate the mean value, and dotted lines indicate the mean value ± 2SD obtained from healthy subjects [8–11], and the range is presented with a mesh.

stabilize the standing posture [12] but to also help with weight bearing in the limb affected by paralysis, muscle weakness, or pain by reducing the vertical floor reaction force [13, 14]. Chen et al. [15] kinematically analyzed the effectiveness of using a cane during gait in post-stroke hemiplegic patients and reported that the peak vertical floor reaction force was observed in the mid-stance phase of the affected-side limb. In the present study, using a handrail might supply the vertical floor reaction force, and this assisted with weight bearing in the unaffected limb with low muscle output. Consequently, there might be an increase in the affected-side single-stance phase duration and unaffected-side step length. Moreover, one of the benefits of using a cane is to assist with driving and braking in the affected limb by increasing the longitudinal floor reaction force [12], but one study reported that the effect of driving and braking is small because the methods of using a cane differ greatly among individuals [13]. In the present study, using a handrail, which is more stable than a cane, could assist with driving and braking in the affected limb, shift the weight to the unaffected side by pulling on the handrail, and increase the support base to maintain the center of gravity during the unaffected-side single-stance phase. These could be the reasons for the longer duration of the affected-side swing phase. Therefore, using a handrail during treadmill gait could assist with affected-limb stability and swing. Additionally, although there were no significant differences in the index values showing the degree of knee extensor thrust and retropulsion of the hip in the affected limb, which are typical abnormal gait patterns for hemiplegic patients, the values tended to decrease when the handrail was used. Knee extensor thrust and retropulsion of the hip are observed with low stability of the affected lower limb [9–11], so we hypothesized that the degree would become smaller with assistance on affected lower limb stability using a handrail. However, in the present study, the degree in some patients was within the normal range [9, 10] even during gait without the handrail, whereas in other patients, it was outside the normal range [9, 10]. Thus, the influence of using a handrail on patients with no obviously abnormal gait patterns even during gait without a handrail was small, so that there were no significant differences in the degree. There were also no significant differences in the index values for circumduction and hip hiking, but the values tended to increase in gait with a handrail. Circumduction and hip hiking are compensatory movements for affected lower limb swing with its reduced toe clearance [16]. The changes in the index values in the gait with a handrail were independent, but overall, their degree tended to increase in the gait with a handrail. Using a handrail, it probably becomes easy to use compensatory movements.

In gait using the cane developed for treadmill gait training in this study (hereafter called "treadmill cane"), the affected-side single-stance phase duration and unaffected-side step length were approximately longer between gait with and without a handrail. Treadmill gait with the treadmill cane suggests that the other parameters may be between with and without a handrail. Moreover, the results of the affected-side step length were the same between gait without a handrail and that with the treadmill cane, but it significantly increased in the gait with a handrail, indicating the treadmill cane has less influence on the affected lower limb swing. The treadmill cane developed in this study is a support tool but is not completely fixed on the ground and it has a multidirectional movable structure, so it is less stable than a handrail. Therefore, it is difficult to shift the weight by pushing and/or pulling the treadmill cane. Yasue et al. [14] reported that the more weight that is applied to a cane, the less weight that is applied to the contralateral lower limb. However, the treadmill cane has a limitation to weight bearing, and gait with the treadmill cane could be a task that is difficult between gait with and without a handrail in terms of assisting with affected lower limb stability. In contrast, the treadmill cane is easier to use compared to a cane during overground gait because it is not necessary to reposition the cane according to the gait cycle. From the point of view of the motor learning theory, for efficiently learning a targeted skill, it is good to prepare for some tasks that are transferable and have different difficulty levels and to practice while converting to these tasks [17]. Thus, it is beneficial to develop a task, the difficulty of which is between gait with and without a handrail, to achieve and improve independent walking with a cane, which is one of the most common rehabilitation goals. Our results show the possibility that treadmill gait training with the treadmill cane developed in this study is difficult between gait with and without a handrail. This could enable treadmill gait training while adjusting the difficulty level of tasks using the treadmill cane and handrail according to walking ability and recovery. The usefulness of recently developed gait training methods using assist robots on a treadmill such as Welwalk WW-1000 (Toyota Motor Corporation, Toyota City, Japan) and Lokomat (Hocoma Inc., Zurich, Switzerland) has been reported [18, 19]. A handrail is supposed to be used during gait training with these robots, but adjusting the difficulty level of gait training using the treadmill cane developed in the present study would be beneficial in facilitating motor learning.

However, this study had a small sample size with restrictive characteristics. One of the inclusion criteria was the ability to walk without a brace to avoid the combined effects of a brace. There was no significant difference between comfortable overground gait velocities with and without a cane, so the treadmill belt speed did not greatly influence the results. However, further examination of patients with more severe abnormalities is needed. Moreover, a limitation of this study is the absence of a kinetic outcome measure, although kinematic analyses were performed. Therefore, further study with a larger number of subjects and conditions is necessary to generalize the effectiveness of the treadmill cane. It is also necessary to clarify the best timing to transfer from a handrail to the treadmill cane, position of the cane, and proper weight of the cane to obtain the maximum effect in clinical settings.

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