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Effects of passive Bi-axial ankle stretching while walking on uneven terrains in older adults with chronic stroke

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ABSTRACT

Many people with stroke experience foot drop while walking. Further, walking on uneven surfaces is a common fall risk for these people that hinder with their daily life activities. In addition, a few years after a stroke, lower-limb exercises become less focused, especially the ankle joint movement. The objective of this study is to determine the gait performance of older adults with chronic stroke on an uneven surface in relation to ankle mobility after a four-week bi-axial ankle range of motion (ROM) exercise session. Fifteen older adults with chronic post-stroke hemiparesis ($N = 15$; mean age = 65 years) participated in a total of 12 bi-axial ankle ROM exercises that consisted of three 30-min training sessions per week for four weeks. Basic clinical tests and gait performance in even and uneven surfaces were evaluated before and after training. Participants with chronic post-stroke hemiparesis showed significantly improved ankle functions, decreased ankle stiffness (from 0.140 ± 0.059 to 0.128 ± 0.067 N·m/°; $p = 0.025$), and increased paretic ankle passive ROMs (dorsiflexion(DF)/plantarflexion(PF): from $27.3 \pm 14.7°$ to $50.6 \pm 10.3°$, $p < 0.001$; inversion(INV)/eversion(EV): $21.7 \pm 9.7°$ to $28.6 \pm 9.9°$; $p = 0.033$) after training. They exhibited significant improvements in the walking performance over an uneven surface, step kinematics (walking speed 0.257 ± 0.17 to 0.320 ± 0.178 m/s; $p = 0.017$; step length: 0.214 ± 0.109 to 0.243 ± 0.108 m; $p = 0.009$), and clinical balance and mobility (Berg balance scale: 47.2 ± 4.7 to 50.1 ± 3.9, $p = 0.0001$; timed-up and go test: 23.9 ± 10.3 to 20.2 ± 7.0 s, $p = 0.0156$). This study is the first research to investigate the walking performance on uneven surfaces in the elderly with chronic stroke in relation to the ankle biomechanical property changes.

1. Introduction

The recovery of mobility in older adults with post-stroke hemiparesis is strongly associated with their living independence (Gronley and Mulroy, 1995; Muren et al., 2008). As a result, their early rehabilitation often focuses on improving their reduced walking ability. In the chronic stage, however, many adults suffer from sustained gait disabilities: reduced walking speed (von Schroeder et al., 1995), asymmetric joint and step kinematics (Balasubramanian et al., 2007; Chen et al., 2005), and reduced joint ROM in the paretic lower limb joints (Beyaert et al., 2015; Higginson et al., 2006; Lewek et al., 2014; Olney and Richards, 1996). In particular, foot-drop syndrome, one of the common hemiparetic ankle impairments, features an excessive equinus during the swing phase in the gait cycle (Burridge and McLellan, 2000; Laufer et al., 2009), which significantly reduces the minimum foot clearance during the swing phase of a gait and consequently increases the risk of fall-related injuries during walking.

Berg et al. reported that walking on an uneven surface is one of the high-risk activities for falls in community-dwelling elderly (Berg et al., 1997) and in older adults with hemiparesis (Burridge et al., 2007). The capability to independently walk on an uneven surface is identified as one of the criteria to distinguish the highest functional improvements in a clinical evaluation, namely, functional ambulation category, which has shown excellent clinical reliability for patients with neurological impairments (Holden et al., 1984; Mehrholz et al., 2007). However, no studies have been conducted that investigate walking over an uneven surface in older adults with chronic stroke, especially in relation to ankle stiffness.

Abbreviations: ROM, range of motion; PF, plantarflexion; DF, dorsiflexion; INV, inversion; EV, eversion; AMT, ankle-movement training.

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Thus, post-stroke hemiparetic walking over an uneven surface is useful for assessing the kinematic and kinetic capacities of the ankle joint, which play a strategically important role in maintaining balance in response to surface irregularities (Runge et al., 1999; Winter, 1995).

Passive ROM at the ankle joint is a practical variable in the clinical walking-capacity evaluation in healthy community-dwelling elderly (Mecagni et al., 2000). Therefore, the traditional rehabilitation approach for a post-stroke hemiparetic ankle joint is focused on the increase in the passive-ankle ROM (Vér et al., 2016) using continuous passive-motion therapy, which has been broadly used in rehabilitation clinics (Thilmann et al., 1991).

To increase the passive neuropathological multi-axial joint ROM, a number of studies have introduced novel equipment for new therapies and its therapeutic effectiveness were tested. Majority of the multi-axial joint therapeutic equipment focuses on the upper limb joints such as the wrist joint (Krebs et al., 2007; Ueki et al., 2012). In reality, the ankle–joint complex is not a simple hinged structure but a bi-axial structure, which functionally comprises the ankle (talocrural) and subtalar (talocalcaneal) joint axes (Wu et al., 2002). In particular, because of the oblique nature of the subtalar joint axis (Jastifer and Gustafson, 2014; Manter, 1941), PF is coupled to supination and INV and DF is coupled to pronation and EV in an orthogonal coordinate system. Few advanced AMT devices are available that have been developed to improve the balance capability and motor control in the paretic ankle for stroke survivors (Deutsch et al., 2001; Farjadian et al., 2014; Forrester et al., 2011). Nevertheless, the bi-axial mechanical characteristics of the anatomical ankle joint complex have not been reflected in the design of such ankle-training devices.

In the chronic stage of a post-stroke paretic ankle, the passive property of the muscle has been changed by muscle contracture and atrophy; hence, ankle joint stiffness increases (Lamontagne et al., 2000; Thilmann et al., 1991). Thus, stretching the ankle muscles help people with stroke increase the ankle ROM, decrease ankle joint stiffness (Bressel and McNair, 2002), and improve paretic walking performance on an even surface. It also increases the walking speed (Kim and Eng, 2003) and increases the paretic step/stride length (Roy et al., 2013). Burridge et al. showed that an ankle neuromuscular stimulation effectively helped patients with a foot drop walk on uneven terrains (Burridge et al., 2007). However, no study has been conducted to analyse if ankle-stretching training can improve the gait performance of older adults with a chronic stroke walking on uneven terrains and consequently to ease symptoms of hemiparetic foot-drop syndrome.

In this study, therefore, the association of bi-axial ankle stretching with ankle stiffness and gait on an uneven surface and the balance performance were investigated by trying to determine whether isokinetic passive bi-axial ankle training reduces the ankle joint stiffness and increases the ankle ROM. It also investigates whether the altered hemiparetic ankle stiffness affects the kinematics during walking on an uneven surface. A custom AMT device was designed and built with bi-axial ankle characteristics. The hypotheses are that the isokinetic passive bi-axial ankle stretching reduces the chronic post-stroke hemiparetic ankle stiffness and improves the clinical balance/mobility measurements and walking performance on uneven terrain. The pre- and post-AMT evaluations include the bi-axial ankle-stiffness-measured footplate reaction forces and moments in the AMT device footplate, clinically defined balance and mobility measurements, and gait performance of the step and joint kinematics while walking on even and uneven surfaces.

2. Methods

2.1. Subjects

Our research staff recruited 15 subjects with post-stroke hemiparesis (age: 64.9 ± 9.0 years; post-onset duration: 9.5 ± 5.6 years) among persons who visited the Outpatient Clinics. The study was approved by the National Rehabilitation Center Rehabilitation Hospital Institutional Review Board, and a signed informed consent form was collected from every participant before test began.

The eligibility criteria were (1) chronic post-stroke hemiparesis, (2) between 50 and 80 years of age, (3) weighing<80 kg, (4) walking independently on a level surface (Functional Ambulatory Category score > 3), and (5) no abnormal muscle tone or slightly increased ankle joint muscle group at the end of the passive ankle ROM only (Modified Ashworth Scale (MAS) < 3). The exclusion criteria included subjects who had (1) complications of orthopaedic disorders, (2) cognitive dysfunctions, or (3) mental illnesses.

2.2. AMT device design and measurement data

The AMT device consisted of the force plate, foot cradle, and supporting frames (Fig. 1A). The ankle DF and PF were implemented using a seesaw-type foot cradle that pivoted along the transverse ankle axis with the height of the malleoli determined from the surface of the footplate in the sagittal plane between two supporting side frames. For the ankle INV/EV, the rear of the foot force plate was attached to the rear supporting beam of the foot cradle and rotated along a 42° tilted subtalar axis relative to the foot cradle. The custom foot force plate consisted of two sandwich-panelled aluminium plates with four bar-type load cells (RS-34, Shezhen Hongrui Sensors Instrument Co., Ltd.) collinearly located between four diagonal corners, which are respectively fastened to the plate inside each side. During training and evaluations, the foot force plate in the AMT device measured the four quadrant (anterior, posterior, medial, and lateral) ground reaction forces sampled at 1 kHz.

The first motor (Model: EC-i40, Maxon Motor Inc., Sachseln, Switzerland) for the AMT DF/PF was located around the lower supporting column, and the motor torque was transmitted via a precise timing belt and high-torque timing pulleys that rotated the foot cradle along the transverse ankle axis. The second motor for the AMT INV/EV was attached to the rear centre of the foot cradle, and it transmitted the rotational torque for AMT INV and EV via a bevel gear to a 90° flexed axis along a 42° tilted subtalar axis in the sagittal plane. The AMT movement speed along the ankle (talocrural) and subtalar (talocalcaneal) axes was 2.14°/s after 14:1 high-power planetary gearheads (GP32HP, Maxon Motor Inc., Switzerland).

2.3. AMT protocol

In the initial AMT session, the subject was asked to comfortably sit on a height-adjustable chair with his/her knees flexed at 90°, place his/her paretic foot on the AMT device footplate, and place his/her non-paretic foot on the height-matched footrest. The paretic foot was fastened to the force plate in the foot cradle using three length-adjustable straps (Fig. 1B).

In one AMT session, four movements were performed along the ankle (talocrural) and subtalar (talocalcaneal) axes while the subject was naturally sitting with his/her knees flexed to 90° without applying any voluntary contractions at a given target ankle joint (Fig. 1C). The simple movements consisted of 20 repetitions of

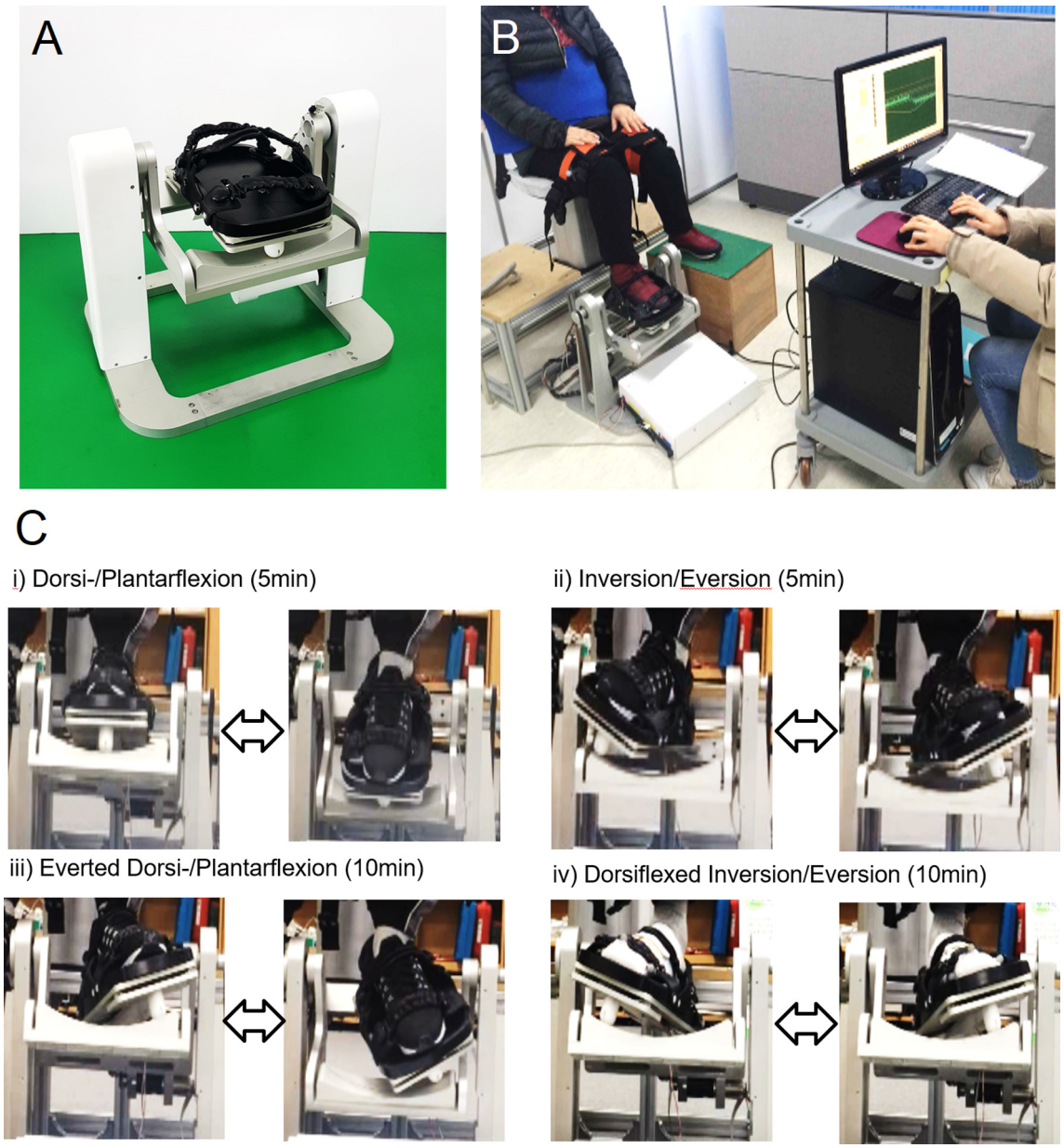

Fig. 1. Custom bi-axial ankle movement training (AMT) device and movement protocol. (A) AMT device, (B) Ankle training environment using AMT device, (C) AMT protocol - Four types of isokinetic passive bi-axial ankle movements; Simple movements of (i) dorsi-/Plantar Flexion (10 times, 5 min), and (ii) Inversion/Eversion; Combined movements (20 times, 10 min); Combined movements of (iii) Everted Dorsi-/Plantar flexion (20 times, 10 min), and (iv) Dorsiflexed inversion/eversion (20 times, 10 min).

the full ROM of both the DF and PF and 20 repetitions of INV and EV. The combined movements consisted of 40 repetitions of both the full ROM everted DF and PF. Then, 40 repetitions of dorsiflexed INV and EV were performed. The full ROMs of the ankle DF/PF and INV/EV were measured at the start of every session. During the repetitions of the simple or complex movements, the AMT device continuously moved without a pause when the direction was changed. One session took approximately 30 min. The subjects participated in a total of 12 AMT sessions at three times per week for four weeks.

2.4. Measurement results in the pre/post evaluations

The pre-/post-AMT evaluations included the following: (1) ankle stiffness in the AMT, (2) gait kinematics on even and uneven surfaces, and (3) clinical balance and mobility measurements of the passive-ankle ROM, namely, the Berg balance scale, timed-up and go test, Functional Ambulatory Category score, and Modified Ashworth Score.

The mean passive-ankle stiffness was evaluated using anteroposterior or mediolateral torque measurements in a custom AMT device foot force plate (Supplement 1). The first ground reaction forces were measured at neutral posture, at 20° of DF/PF, and at 20° of INV/EV. Subsequently, the anteroposterior and mediolateral ankle torques were calculated along the ankle (talocrural) and subtalar (talocalcaneal) axes. Finally, the mean ankle stiffness at a given ankle axis was obtained in the pre-/post-AMT evaluations. The AMT device measured four quadrant (anterior, posterior, medial, and lateral) ground reaction forces sampled at 1 kHz.

In the pre-/post-AMT gait evaluations, the subjects repeated the even-surface walking trials at least four times on a 1.5 m × 10 m even walkway covered with industrial carpeting at a comfortable speed. They then repeated the uneven-surface walking trials at least four times, yielding at least 20 valid steps per surface type

and subject. In accordance with a previous study, the uneven surface was created using randomly arranged triangular wooden prisms (H 1.5 cm × W 3.5 cm × L 6–12 cm) placed under a 1.5 m × 10 m strip of industrial carpeting with a surface texture identical to that of the even surface (Richardson et al., 2004). The kinematic data were recorded using a VICON motion-capture system sampled at 100 Hz with 24 reflective passive markers on the lower limbs of the subject. These markers were placed on the anterior superior iliac spine, posterior superior iliac spine, thigh, knee, medial knee, tibia, ankle, medial ankle, toe, and heel following the plug-in-gait model, as recommended by VICON for the lower limbs and pelvis (Oxford Metrics, Oxford, England). The kinematic data were processed by Visual 3D (C-Motion, Germantown, MD, USA) using a fourth-order zero-lag Butterworth low-pass filter with 6- and 20-Hz cut-off frequencies. The joint kinematics were post-processed to calculate the hip flexion/extension and abduction/adduction, knee flexion/extension, ankle DF/PF, and INV/EV. The step kinematics on the paretic and non-paretic sides were processed to acquire the walking speed at the body centre of mass, step length, step width, and step time, as defined in a previous study (Richardson et al., 2004).

2.5. Statistical analysis

Descriptive statistics were obtained for clinical and kinematic variables to depict the demographic characteristics, step, and joint kinematics of the subjects during a gait on even and uneven surfaces and ankle stiffness. The hypotheses were tested by comparing the gait and step parameters between the pre- and post-AMT interventions using a paired two-sided *t*-tests in SPSS V21.0.0.1 (IBM Corporation, Chicago, Illinois, USA), where $p < 0.05$ was considered as statistically significant.

3. Results

3.1. Demographic characteristics of subjects

The demographic characteristics of the subjects are listed in Table 1. All 15 participants with chronic post-stroke hemiparesis completed all 12 sessions without any complications caused by the test equipment or test procedure. No adverse events occurred during the AMT sessions. No gender bias or obesity effects existed among the participants (six females; body mass index: 26.3 ± 2.8). The initial clinical evaluation showed that all participants were able to independently walk on a level surface (Functional Ambulatory Category score: 5.9 ± 0.4), and during the passive-ankle movements, the increase in the muscle tone was minimal or weak at the end of the ankle ROM (MAS: 0.5 ± 0.5).

3.2. Ankle stiffness and clinical balance measurements

The mean ankle stiffness during the DF/PF movement significantly decreased after the AMT (pre-AMT: 0.140 ± 0.059 N·m/°, post-AMT: 0.128 ± 0.067 N·m/°; $p = 0.025$) (Fig. 2). Significant increases were observed in the Berg balance scale (from 47.2 ± 4.7 to 50.1 ± 3.9; $p = 0.0001$), and significant time reductions occurred in the TUG test (from 23.9 ± 10.3 to 20.2 ± 7.0 s; $p = 0.0156$) (Fig. 3A). The mean passive paretic ROM range of the DF/PF significantly increased from 27.3 ± 14.7° to 50.6 ± 10.3° ($p < 0.001$) (PF: from 16.8 ± 15.6° to 39.3 ± 10.2°; $p < 0.001$; DF: from 10.4 ± 4.3° to 11.3 ± 3.5°; $p = 0.400$). In addition, the mean passive ROM range of the INV/EV increased from 21.7 ± 9.7° to 28.6 ± 9.9° ($p = 0.0338$) (INV: from 13.9 ± 7.4° to 17.6 ± 6.5°; $p = 0.073$; EV: from 7.8 ± 3.9° to 11.0 ± 4.1°, $p = 0.062$) (Fig. 3B).

3.3. Kinematic changes during gait

AMT effects were observed on the total ROMs in the hip, knee, and ankle joints during both even and uneven gait cycles. On the even surface, significant kinematic ROM increases were observed in the hip paretic flexion/extension (from 30.1 ± 9.4° to 34.9 ± 7.8°; $p = 0.011$), paretic abduction/adduction (from 12.2 ± 2.9° to 13.3 ± 2.8°; $p = 0.029$), paretic and non-paretic knee flexion/extension (paretic: from 40.4 ± 13.4° to 44.5 ± 11.7°; $p = 0.043$; non-paretic: from 54.1 ± 15.9° to 62.3 ± 6.5°; $p = 0.034$), and non-paretic ankle DF/PF (from 23.6 ± 5.6° to 27.2 ± 5.3°; $p = 0.029$). On the uneven surface, significant kinematic ROM increases were observed in the paretic and non-paretic hip and knee flexion/extension (paretic hip: from 27.1 ± 9.6° to 31.6 ± 9.4°; $p = 0.034$; knee: from 35.9 ± 13.2° to 40.4 ± 12.6°; $p = 0.029$; non-paretic hip: from 36.0 ± 10.0° to 42.9 ± 9.6°; $p = 0.002$; knee: from 50.8 ± 13.8° to 57.4 ± 10.7°; $p = 0.012$) and in the paretic ankle DF/PF (from 15.9 ± 6.7° to 18.6 ± 7.8°, $p = 0.046$) (Table 2). Fig. 4 shows the paretic and non-paretic hip, knee, and ankle joint kinematics during one gait cycle on the even and uneven surfaces.

Table 3 lists the step kinematics during the paretic and non-paretic stance phase on the even and uneven surfaces. On the even

Table 1
Demographic characteristics of subject with hemiparesis.

Subject with hemiparesis (n = 15)	Gender (F; M)	Age (years)	Height (cm)	Weight (kg)	BMI	Affected side (L; R)	Time since Stroke (month)	MAS	FAC
1	M	76	166	62	22.5	R	146.4	1	6
2	F	68	157	57	23.1	R	109.3	0	6
3	F	65	145	50	23.8	R	94.9	0	6
4	M	52	174	80	26.4	L	207.3	0	6
5	M	74	164	65	24.2	R	90.9	0	6
6	F	78	147	60	27.8	L	105.1	0	6
7	M	52	164	70	26.3	L	52.8	1	6
8	M	73	159	62	24.5	L	48.1	0	6
9	M	68	167	74	26.5	L	145.7	1	5
10	M	74	171	77	26.3	R	42.3	0	6
11	F	56	151	57	25.0	L	101.7	1	6
12	M	61	164	65	24.2	L	36.5	0	6
13	M	59	170	70	24.2	L	277.4	1	6
14	F	54	158	76	30.4	L	142.6	1	6
15	F	63	158	70	28.0	L	195.5	1	5
Mean	**6F; 9 M**	**64.9**	**161.0**	**66.3**	**25.5**	**10L; 5R**	**114.4**	**0.5**	**5.9**
S.D.		9.0	8.6	8.5	2.1		67.1	0.5	0.4
Minimum		52	145	50	22.5		36.5	0	5
Maximum		78	174	80	30.4		277.4	1	6

FAC denotes functional ambulation category score, MAS modified denotes Ashworth Score, BMI denotes Body Mass Index

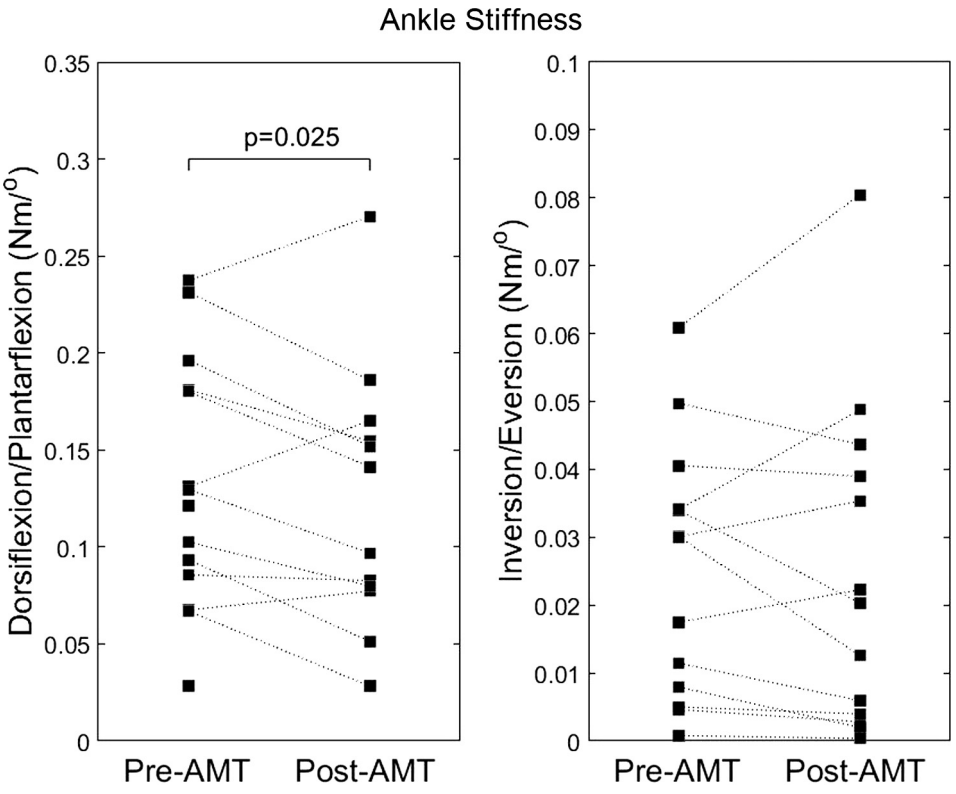

Fig. 2. Changes in ankle stiffness between pre/post-AMT evaluations; Dorsi-/Plantarflexion (left), In-/Eversion (right). * denotes the significance level ($p < 0.05$).

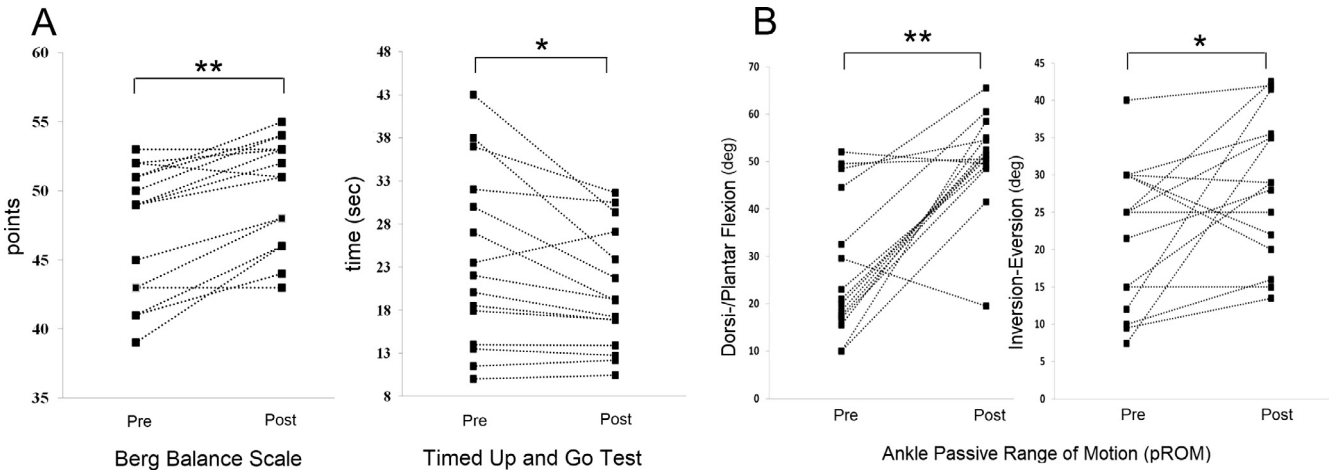

Fig. 3. Changes in clinical measures between pre/post-AMT evaluations. (A) Balance and mobility capacity measures; Berg Balance Scale (left), Timed Up and Go test (right), (B) clinical passive range of motion (pROM); Dorsi-/Plantar Flexion (left), Inversion/Eversion (right). * denotes the significance level ($p < 0.05$), ** denotes the significance level ($p < 0.01$).

surface, no significant kinematic changes occurred in the steps in both paretic and non-paretic stance limbs. However, on the uneven surface, both the walking speed and step length significantly increased after completing the AMT intervention in the paretic stance limb (walking speed: from 0.257 ± 0.170 to 0.320 ± 0.17 m/s; $p = 0.017$; step length: from 0.214 ± 0.109 to 0.243 ± 0.108 m; $p = 0.009$).

4. Discussion

This study is the first research to show the effects of walking on uneven terrain in older adults with chronic stroke in relation to ankle biomechanical property. Because ankle stiffness decreases after bi-axial ankle stretching training, improved ankle mobility in older adults with chronic stroke influences the clinical balance measurements, particularly the gait performance on an uneven surface. To perform safe and stable walking on an uneven terrain, healthy adults often adopt increased ROM during gait in the hip and knee flexion and ankle DF that improve minimum foot clearance (Gates et al., 2012), and increased walking speed and step length during uneven surface walking (MacLellan and Patla, 2006). Consequently, bi-axial isokinetic passive-ankle stretching is an adequate training to reduce ankle stiffness, as measured during the passive-ankle movements on the AMT, thus to improve walking on uneven terrains.

All hemiparetic participants were actively encouraged to attend all AMT sessions and were contented with the bi-axial ankle-stretching training results. Because the post-AMT joint ROM of

Table 2
Joint range of motion on the paretic and non-paretic hip, knee and ankle joints during the paretic and non-paretic swing phase on even and uneven surfaces before and after the isokinetic passive bi-axial ankle movement intervention using AMT.

Joint ROM (deg)		Paretic Side			Non-Paretic Side		
		Pre-AMT	Post-AMT	p	Pre-AMT	Post-AMT	p
Even Surface	Hip Flexion-Extension	30.1 ± 9.4	34.9 ± 7.8	**0.011**	40.0 ± 11.6	27.0 ± 5.3	0.053
	Hip Abduction-Adduction	12.2 ± 2.9	13.3 ± 2.8	**0.029**	14.6 ± 5.3	14.5 ± 5.0	0.088
	Knee Flexion-Extension*	40.4 ± 13.4	44.5 ± 11.7	**0.043**	54.1 ± 15.9	62.3 ± 6.5	**0.034**
	Ankle Dorsi-Plantarflexion*	18.7 ± 5.9	21.5 ± 7.6	0.214	23.6 ± 5.6	27.2 ± 5.3	**0.029**
	Ankle Inversion-Eversion	12.6 ± 4.7	14.9 ± 5.8	0.065	11.7 ± 2.4	13.3 ± 3.6	0.932
Uneven Surface	Hip Flexion-Extension*	27.1 ± 9.6	31.6 ± 9.4	**0.034**	36.0 ± 10.0	42.9 ± 9.6	**0.002**
	Hip Abduction-Adduction	11.8 ± 5.5	12.3 ± 3.6	0.500	14.1 ± 4.3	15.3 ± 5.5	0.235
	Knee Flexion-Extension*	35.9 ± 13.2	40.4 ± 12.6	**0.029**	50.8 ± 13.8	57.4 ± 10.7	**0.012**
	Ankle Dorsi-Plantarflexion	15.9 ± 6.7	18.6 ± 7.8	**0.046**	22.2 ± 7.0	24.1 ± 5.4	0.283
	Ankle Inversion-Eversion	12.7 ± 6.3	13.9 ± 6.1	0.262	12.7 ± 3.4	14.7 ± 6.1	0.123

Bold values denote significance level of $p<0.05$ between Pre- and Post-AMT.
* denotes significant joint kinematic differences between paretic and non-paretic sides ($p < 0.05$).

the hip and knee flexion/extension was improved during the gait on an uneven surface, their minimum foot clearance increased, thus, minimising their foot-drop syndrome during a gait. In particular, the constrained ankle-stretching mode in the AMT effectively minimised the foot-drop syndrome symptoms in the paretic ankle while walking on an uneven surface. The results show that the post-AMT ankle stiffness of the EV and DF remained unchanged, whereas the post-AMT stiffness of the INV and PF stiffness decreased. Thus, the net ankle torque decreased at the ankle joint that acted on the foot drop during the swing phase of the gait cycle as the corresponding ankle stiffness decreased, which affected the ankle plantar flexor and inverter acting on the foot-drop syndrome. This result suggests that the selective passive ankle stretching using the bi-axial AMT movements minimised the imbalance in the post-stroke hemiparetic ankle torque at the ankle joint complex along the ankle and subtalar joints.

The passive-ankle stiffness is determined by the passive properties of four large muscle groups around the ankle joint, namely, tibialis anterior, peroneus longus, and the triceps surae muscles, i.e. soleus and gastrocnemius. Ankle stiffness has been measured in previous studies during quiet standing (14.9 N·m/°) (Winter et al., 2001), in seated robotic trainer (post-training PF: 0.174 ± 0.008 N·m/°) (Roy et al., 2013), and in paretic passive-ankle stiffness (DF: 0.43 N·m/°) (Lamontagne et al., 2000). Our present study defined the ankle stiffness as the mean stiffness of moderate DF and PF (Supplement 1), and the post-AMT stiffness decreased during the passive DF/PF as the passive tension of the ankle muscle decreased (pre-AMT: 0.140 ± 0.059 N·m/°, post-AMT: 0.128 ± 0.067 N·m/°; $p = 0.025$). The use of the AMT device made possible the bi-axial and passive-ankle stretching; thus, the passive AMT movement provided specific one-to-one matched training to decrease the target joint stiffness in the ankle joint complex.

Walking on uneven terrains is useful to identify the pathological gait limitations under a realistic challenging environment and to reveal the kinematic effectiveness of a novel intervention on daily-life activities. In our study, the results from the uneven-terrain gait successfully showed that the post-AMT joint kinematics was effective because the walking speed and step length significantly increased. In previous studies, healthy adults modified their step and joint kinematics and neuromuscular activities during walking on an uneven surface; reduced their walking speed and step length (Menz et al., 2003), increased their hip and knee flexion (Gates et al., 2012), and increased their gastrocnemius and soleus muscles (MacLellan and Patla, 2006). Furthermore, researchers have used uneven gait results as an evaluation method to prove the effectiveness of clinical interventions for the elderly with neurological disorders, namely, diabetic peripheral neuropathy (Richardson et al., 2004), and muscle stimulation to patients with hemiparesis (Burridge et al., 2007). In these studies, increased walking speed and step length required more unilateral flexions at the hip, knee, or ankle joints during the swing phase that possibly manipulate a sufficient minimum foot clearance during gait on an uneven surface (Hawkins et al., 2017). Therefore the gait performance on an uneven surface in this study showed promising effects on the kinetic chain activities of lower limb when walking (McPoil and Knecht, 1985), such that the post-AMT paretic swing limb increased entire lower limb joint ROMs.

In summary, our results reveal that the four-week ankle-stretching training with isokinetic passive bi-axial joint movements using the AMT was effective in decreasing the DF/PF ankle stiffness, thus improving the clinical balance and mobility measurements, and finally improved the joint and step kinematics while walking on uneven terrains. We believe that this is the first study to provide the clinical usefulness of the gait evaluation on an uneven terrain in people with chronic stroke in terms of biomechanical property improvement and ankle stiffness. Correspondingly the bi-axial AMT is a practical approach to palliate foot drop symptom during activities of daily living in the older adults with chronic stroke.

4.1. Study limitations

The current protocol mainly focused on the mitigation of the soleus muscle that is involved in the foot-drop syndrome. However, more clinically applicable and potentially effective AMT stretching protocols may be available. Variations in the intensity (e.g. degree of movements), duration (e.g. training time), and frequency (e.g. times per week) may affect the post-AMT outcomes. In addition, further investigation on the effects of stretching other target ankle muscles, e.g. whole triceps surae, is necessary.

This study focused only on the passive-ankle stretching training, which realised effective consequences in clinical balance and gait in people with a chronic stroke. The post-AMT kinematic changes were assumed to be closely related to the identified AMT effects as persistent gait training. However, careful interpretation on the results is necessary when a control group is absent as in this study, and further investigation on the other types of the bi-axial ankle intervention is necessary in people with chronic stroke, such as ankle-strengthening training. This additional training may promote active-ankle movement as a persistent lower limb-rehabilitation treatment for people with post-stroke hemiparesis.

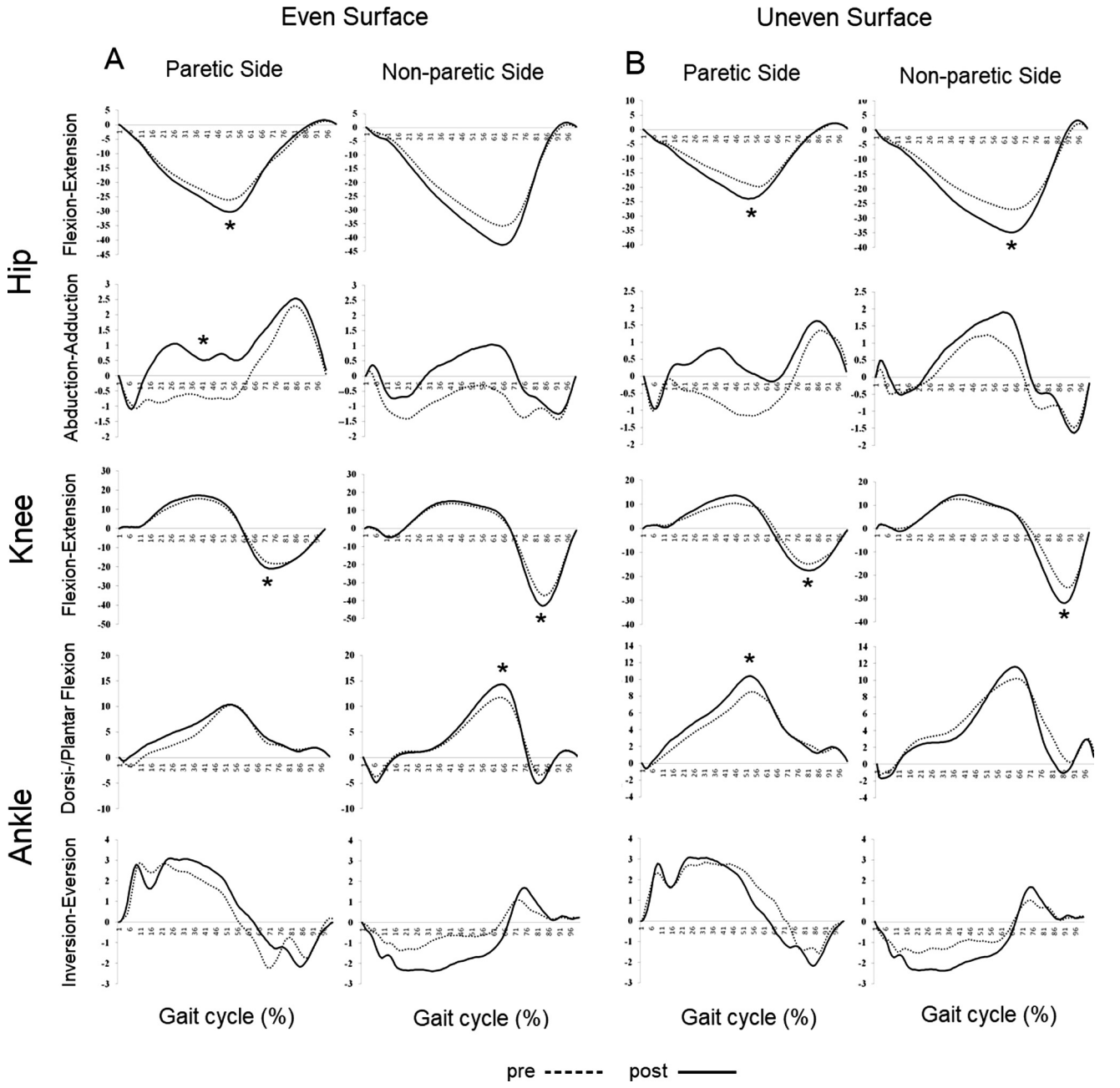

Fig. 4. Joint range of motion on the paretic and non-paretic hip, knee and ankle joints during one gait cycle in pre/post gait evaluation. (A) on even surface; paretic side (left), non-paretic side (right) (B) on uneven surface; paretic side (left), non-paretic side (right). Dotted line indicates pre-AMT joint kinematics, Solid line indicates post-AMT joint kinematics. * denotes the significance level ($p < 0.05$), dotted line.

Table 3
The step kinematics during the paretic and non-paretic stance phase on even and uneven surfaces before and after the isokinetic passive bi-axial ankle movement intervention using AMT.

		Paretic Side					Non-paretic Side				
		Pre-AMT		Post-AMT		p	Pre-AMT		Post-AMT		p
		Mean	SD	Mean	SD		Mean	SD	Mean	SD	
Even Surface	Walking Speed (m/s)	0.390	0.189	0.404	17.8	0.440	0.526	0.240	0.581	0.215	0.100
	Step Length (m)	0.298	0.108	0.319	9.2	0.059	0.314	0.112	0.329	0.099	0.375
	Step Width (m	0.167	0.052	0.171	5.0	0.390	0.176	0.051	0.180	0.046	0.509
	Step Time(sec)	0.840	0.167	0.837	143.5	0.866	0.565	0.274	0.563	0.175	0.967
UnevenSurface	Walking Speed (m/s)	**0.257**	0.170	**0.320**	0.178	**0.017**	0.359	0.226	0.404	0.246	0.101
	Step Length (m)	**0.214**	0.109	**0.243**	0.108	**0.009**	0.250	0.106	0.267	0.108	0.128
	Step Width (m)	0.202	0.064	0.209	0.076	0.658	0.204	0.062	0.208	0.054	0.707
	Step Time(sec)	0.904	0.181	0.829	0.194	0.614	0.740	0.278	0.678	0.257	0.240

Bold values denote significance level of $p<0.05$ between Pre- and Post-AMT.

Conflict of interest statement

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author disclosures

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. This is an original contribution to which the authors have contributed equally in all phases of the research. The material within has not been and will not be submitted for publication elsewhere as a paper.

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Clinical Trial Registration

This study was registered in Clinical Research Information Service of Korean National Institute of Health.

- Website: http://cris.cdc.go.kr/cris/en/use_guide/cris_introduce.jsp,
- Reference number : KCT0002965

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.014.

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