Technology-Assisted Ankle Rehabilitation Improves Balance and Gait Performance in Stroke Survivors: A Randomized Controlled Study With 1-Month Follow-Up

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***Abstract*—Many stroke survivors have limited ankle range of motion (ROM) caused by weak dorsiflexors and stiff plantarflexors. Passive ankle stretching exercises with physical therapists or a stretching board are usually recommended, but these treatments have some limitations (e.g., cost and availability of physical therapists). In this paper, we assessed the results of ankle stretching exercises delivered by a robotic ankle stretching system called motorized ankle stretcher (MAS) that we developed or by a stretching board on ankle ROM, balance control, and gait performance. The 16 stroke survivors were randomly assigned to an intervention group (IG) or a control group (CG) and participated in seven sessions of dorsiflexion stretching exercises for three-and-a-half consecutive weeks. Laboratory assessments included pre-assessment (baseline at the beginning of the first exercise session), post-assessment (at the end of the seventh exercise session), and retention assessment (one month after the seventh exercise session). All assessments included ankle ROM for the affected side, static/dynamic balance control with a sensory organization test (SOT), walking speed, walking cadence, and step length for the affected and unaffected sides. During seven sessions of ankle stretching exercises, the IG performed them using the MAS, and the CG used a stretching board. The IG significantly improved ankle ROM, SOT scores (i.e., static/dynamic balance control), walking speeds, walking cadences, and step lengths for the unaffected side after completing the seven exercise sessions of ankle stretching exercises and maintained the enhancements at the retention assessment. The CG did not significantly improve across the majority of outcome measures except for the SOT scores between the pre-assessment and retention assessment. Future work will investigate the ideal intensity, frequency, and duration of exercising with the MAS. Our research on technology-assisted ankle rehabilitation, which can ascertain the level of persistent improvement, long-term performance retention, and carry-over effects in stroke survivors, can be used to inform future designs.**

***Index Terms*—Stroke, ankle rehabilitation, ankle range of motion, sensory organization test, balance and gait performance.**

I. INTRODUCTION

STROKE, the fifth-leading cause of mortality in the U.S. [1], affects 15 million people worldwide annually [2]. It is the second-leading cause of death for people aged 60 or older and the fifth-leading cause of death for people aged between 15 and 59 globally [3].

Limited ankle range of motion (ROM) for the affected side is the common sequela in stroke survivors. It is caused by weakness of dorsiflexors (e.g., tibialis anterior, extensor halluces longus, and extensor digitorum longus) and stiffness of plantarflexors (e.g., gastrocnemius, soleus, tibialis posterior, flexor halluces longus, and flexor digitorum longus) following stroke [4]. Ankles are located close to the body's base of support and assist in controlling balance [5]. Limited ankle ROM in most stroke survivors impairs balance control, which is a major risk factor for falls [6], [7]. Functional gait and symmetric gait rely on ankle ROM and well controlled contraction of dorsiflexors and plantarflexors [8]. Normal gait requires a minimum 10° of dorsiflexion [4], and plantarflexors (e.g., gastrocnemius and soleus) commonly generate forward propulsion during the push-off phase in locomotion [9], [10]. Due to limited ankle ROM and abnormal contraction of dorsiflexors and plantarflexors, most stroke survivors manifest slow walking speed, reduced cadence, and shortened step length, which are common indicators of abnormal gait patterns [4], [11]. The recovery of impaired ankle motion and muscles (e.g., dorsiflexors and plantarflexors) to improve balance control and gait performance has received attention in stroke rehabilitation [12]–[14].

Therapeutic regimens involving ankle stretching exercise are widely utilized for treating limited ankle ROM in stroke survivors. Passive ankle stretching exercises can be applied manually by physical therapists [15], [16], external devices (e.g., stretching board) [17], [18], and robotic systems [19]–[25]. The objectives are to decrease muscle tone, improve soft-tissue extensibility, and increase ankle ROM for the affected side [14], [22], [26], [27]. Although

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manual passive ankle stretching by moving the impaired ankle joint through its ROM is relatively easy in clinical settings, clinical studies have shown insignificant improvements on ankle ROM [15], [16]. Furthermore, the limited availability of physical therapists and the labor-intensive efforts to deliver manual therapy can prohibit stroke survivors from undertaking clinical regimens [15], [22], [28]–[30]. Thus, stretching boards [17], [18] and robotic systems [19]–[25] are often substituted. Stretching boards have benefits (reducing the therapist's labor) and limitations (e.g., difficult to adjust the minutely applied angle; no safety bar). Robotic systems have benefits (the therapist can help more patients at less cost and labor [31]) and limitations (e.g., complicated to use and repair; cost). Previous studies have indicated that after stroke survivors received robot-assisted therapy for short (hours to days) and long (weeks to months) periods, ankle ROM and gait speed increased and passive stiffness of the ankle decreased [23]–[25], [32]. Despite previous studies which demonstrated that weight-bearing ankle stretching exercises can result in improving muscle tones and ankle torques compared to non-weight-bearing ankle stretching exercises (e.g., [33], [34]), most existing robotic systems support ankle stretching exercises, whereas supine or sitting positions provide no weight-bearing benefits (see [35] for review).

Recently we developed a low-cost, easy-to-use ankle rehabilitation system, which we call a Motorized Ankle Stretcher (MAS) [36], that provides passive weight-bearing ankle stretching exercises. Our feasibility study showed that stroke survivors increased ankle ROM after completing ankle stretching exercises with the MAS over a single exercise session of 20 exercise repetitions [36]. Based on this promising result, this investigation has two objectives: 1) compare the benefits of the MAS regimen with the stretching board regimen, and 2) quantitatively assess the results of long-term ankle stretching exercises with the MAS and investigate the carry-over effects of improved ankle ROM, balance control, and gait performance in stroke survivors.

II. METHODS

A. Motorized Ankle Stretcher (MAS)

The MAS consists of two footplates with one linear in-line actuator (con50; Concens, Esbjerg, DK) underneath each one, an actuator controller (con50; Concens, Esbjerg DK), a microcontroller (ATmega 128; Atmel, San Jose, USA), a safety bar, and custom software as shown in Fig. 1. The manufacturers of the linear in-line actuator specify a maximum load range of 3.1 kN for each footplate. Each actuator connects to each footplate through a parallel joint mechanism using two universal joints. In Fig. 1(a), actuators 1 and 2 generate dorsiflexion and eversion, respectively, and support the loads imposed on the footplates while the stroke survivor performs dorsiflexion and/or eversion exercises. The microcontroller converts the desired angular motion of the footplates to command signals (DC voltages from 0 to 5V) and sends them to the actuator controller that positions and controls the actuators. The dimensions of the system hardware (two footplates, two linear in-line actuators, actuator controller, and microcontroller) are 34 cm × 61 cm × 11 cm; a crank-slider mechanism minimizes the size of the required hardware.

ankle: Normal
Dorsiflexion: 0
Eversion: 0
Speed: 1
Repeat: 5
Hold Time: 10
Relax Time: 10

Fig. 1. MAS. (a) Hardware. (b) Custom software. (c) System prototype.

The custom software using Microsoft Visual Basic shown in Fig. 1(b) operates the footplates based on the exercise parameters that are transferred to the microcontroller through serial data communications with a wired connection. The exercise parameters are: exercise angle, motion speed, number of exercises, hold time at any selected exercise angle, and relax time at the initial position (0° for dorsiflexion and eversion) of the footplates as shown in Fig. 1(a). The maximum exercise angle is 50° for dorsiflexion and 25° for eversion. The moving speed of the footplates ranges between 0.5 and 6.0°/s. The custom software's safety feature is a stop and pause button that returns the footplates to their initial positions. The developed prototype (56 cm × 75 cm × 15 cm) housing the system hardware is shown in Fig. 1(c).

B. Participants

The sixteen stroke survivor participants were randomly assigned to one of two groups of eight (intervention group (IG) and control group (CG)). All participants 1) were at least 6 months post-stroke survivors; 2) scored between 4 and 6 in the Functional Ambulation Category (FAC); 3) scored between 5 and 14 in the National Institutes of Health Stroke Scale (NIHSS) (representing a mild/moderate stroke); and 4) could stand for 5 min and walk 10 m independently without assistive instruments (i.e., walker or cane); this last criterion was included for balance and gait assessments. Participants were excluded if they had: 1) a functionally significant musculoskeletal dysfunction; 2) any neurological disease other than stroke; or 3) peripheral sensory disease (e.g., peripheral neuropathy, Type 2 diabetes, vestibular disorder, etc.). Prior to the study, all participants underwent criteria-related assessments to confirm they could safely use the MAS and

TABLE I

STATISTICAL ANALYSIS RESULTS OF DEMOGRAPHIC AND CLINICAL CHARACTERISTICS OF THE PARTICIPANTS (N = 16) BETWEEN TWO GROUPS. BMI: BODY MASS INDEX; NIHSS: NATIONAL INSTITUTES OF HEALTH STROKE SCALE; FAC: FUNCTIONAL AMBULATION CATEGORY

	IG	CG	*P*-value
Age (years)	58.5±9.4	53.9±6	0.261
Gender (male, %)	Male, 75%	Male, 62.5%	-
Height (cm)	173.1±9.2	174.6±8.9	0.746
Weight (kg)	89±21.8	80.6±22.5	0.462
BMI (kg/m^2)	29.6±6.4	26.8±7	0.410
Time after stroke (month)	42.9±12.8	47.5±26	0.658
Affected side (left, %)	Left, 62.5%	Left, 75%	-
NIHSS (score)	6.1±0.8	5.9±1	0.680
FAC (score)	5.5±0.9	58.5±0.8	1.000

fully perform the ankle stretching exercises. All participants were not participating in any physical therapy program at the time of enrollment, and they were asked not to start any new physical activity or therapy until after the study. Table I in the Results section reports the characteristics of the participants.

The study protocol was approved by the University of Houston Institutional Review Boards, which is in accordance with the Helsinki Declaration. Informed consent was obtained from all participants prior to the study.

C. Experimental Protocol

The experimental design included laboratory assessments and seven sessions of ankle dorsiflexion stretching exercises with the MAS for the IG and the stretching board for the CG. The laboratory assessments included pre-assessment (baseline, before the first exercise session), post-assessment (after the seventh exercise session), and retention-assessment (one month after the seventh exercise session). All participants completed a total of seven exercise sessions two days per week for three and a half consecutive weeks. Consecutive exercise sessions per week were separated by two or three days of rest.

Each assessment quantified participants’ ankle ROM for the affected side, static/dynamic balance control, and gait performance. Two inertial measurement units (IMUs; Trigno™IM, Delsys, Natick, MA, USA) measured ankle ROM for the affected side. The two IMUs were attached to the middle of the lower limb (on the skin over the middle of the tibia at the anterior side) and to the top of the affected foot (on the skin over the intermediate cuneiform bone) as shown in Fig. 2. After attachment, each participant sat on a chair and rested their legs on another chair in front (knee extension position with nearly 90° between the shank and foot confirmed by a goniometer) as shown in Fig. 2. The knee extension position shown in Fig. 2 was considered as an initial position for ankle ROM measurements. The participant then moved the affected foot up toward the shank as far as possible without knee flexion for 5 s. All participants completed 3 trials of the ankle ROM measurement, and the consecutive trials were separated by a 20 s rest period.

Fig. 2. Initial ankle position for measuring ankle ROM.

A sensory organization test (SOT) using a Balance Master®(NeuroCom International Inc., Clackamas, OR, USA) assessed participants’ static/dynamic balance control which is an effective tool for measuring balance in stroke patients [37]. The SOT consisted of six conditions (1: Normal vision and fixed support; 2: Absent vision and fixed support; 3: Sway-referenced vision and fixed support; 4: Normal vision and sway-referenced support; 5: Sway-referenced support and absent vision; and 6: Sway-referenced vision and sway-referenced support), and each condition consisted of 3 trials. During the SOT, all participants wore a safety harness and stood on the force plate of the Balance Master®by maintaining an upright posture with arms crossed their chest. All participants completed 18 trials (3 trials for six conditions). Each trial lasted 20 s, and consecutive trials were separated by a 20 s rest period.

A GAITRite floor mat (CIR Systems Inc., Franklin, NJ, USA) equipped with pressure sensors underneath the 5.12 m mat assessed gait performance. All participants walked on the floor mat at a self-selected comfortable walking speed for 3 trials. A human spotter stood next to each participant in case of sudden loss of balance and falls. Each trial was separated by a 20 s rest period.

The protocols for the training sessions were developed based on a study that reported positive effects after stretching in stroke survivors [38]. The IG and CG completed seven sessions of ankle stretching exercises (i.e., dorsiflexion stretching exercises) with the MAS and the stretching board, respectively. Each training session included 2 sets of dorsiflexion stretching exercises, and each stretching set consisted of 10 exercise trials. Each trial was separated by a 10 s rest period while standing, and each stretching set was separated by 10 min of seated rest between sets. Each training session lasted approximately 30 min.

During each trial with the MAS, the two footplates of the MAS generated an identical dorsiflexion angle (i.e., the measured ankle ROM for the affected side at pre-assessment) for 30 s (Fig. 3) and then returned to their initial neutral standing positions at a 2°/s moving speed (stretching gradually applied and released). During each exercise trial with the stretching board, CG participants were instructed to stand on the stretching board for 30 s and then step off and take 10 s of rest by standing on the floor.

The CG and IG were instructed to keep their knees fully extended in an upright position during the stretching sets and to either touch or hold onto the safety bar during each trial. At the beginning of each set, the stretching angle was set to the angle of the previous trial, and increased by 20% (approximately 2°) if the participant reported a score less than 7 (i.e., somewhat difficult) of visual analog scales (VAS) (from 0 (no exertion) to 10 (maximal exertion) [25].

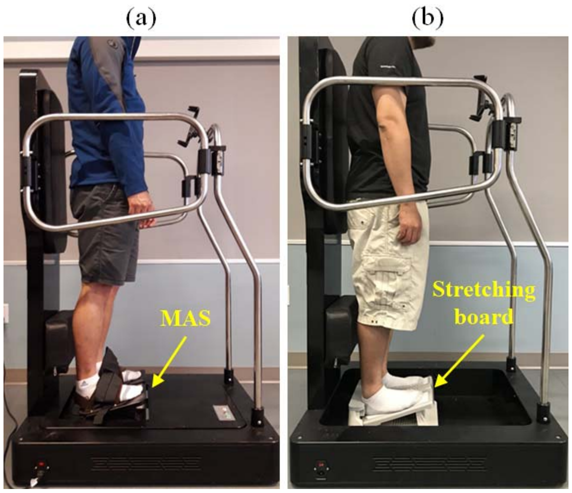

Fig. 3. (a) Dorsiflexion exercises with the MAS. (b) Dorsiflexion exercises with the stretching board.

D. Data and Statistical Analysis

Ankle ROM for the affected side, a SOT score, walking speed, walking cadence, and step length for the affected and unaffected sides were analyzed to evaluate the effects of the ankle stretching exercises for both groups as a function of the assessment. To compute ankle ROM, MATLAB (The MathWorks, Natick, MA) processed the recorded IMU signals using a sensor fusion algorithm [39]. Ankle ROM in degrees was defined as a range of dorsiflexion from an initial position (nearly 90° between the shank and foot) to a maximum dorsiflexion position as shown in Fig. 2. The SOT score obtained from the Balance Master®and ranged from 0 to 100, (100 indicates no body sway and 0 indicates a fall) [40]. Gait parameters (walking speed, walking cadence, and step length for the affected and unaffected sides) were obtained from the GAITRite.

All statistical analysis was performed by SPSS (IBM Corp., Armonk, NY, USA). An independent t-test was conducted to compare the two groups' demographic and clinical characteristics (NIHSS and FAC). Normality of distribution and sphericity of variance of all outcome measures (ankle ROM; SOT score; walking speed; walking cadence; and affected and unaffected step length) were evaluated using a Shapiro-Wilk test and Mauchly's test, respectively. A repeated measures analysis of variance (ANOVA) determined the main effects of groups (IG and CG) and periods (the pre-, post-, and retention-assessment), and the interactions (group × period) for all outcome measures. Each group's main effects, periods, and interactions were tested using an F test. Post hoc analysis for all outcome measures was conducted with a Bonferroni's method to determine which factors influenced the main and interaction effects. The level of significance was defined at the $p < 0.05$ level.

TABLE II

STATISTICAL ANALYSIS RESULTS OF ALL OUTCOME MEASURES FOR GROUP (G), PERIOD (P), AND INTERACTION (G × P). $*$ P < 0.05 AND $**$ P < 0.01

Dependent variable	Effects	DF	F value	Pr>F
Ankle ROM (deg)	G	1, 7	0.000	0.984
	P	2, 14	5.010	0.023*
	G × P	2, 14	7.844	0.005**
SOT (score)	G	1, 7	8.573	0.022*
	P	2, 14	10.721	0.002**
	G × P	2, 14	7.813	0.005**
Walking speed (cm/s)	G	1, 7	0.198	0.669
	P	2, 14	5.401	0.018*
	G × P	2, 14	3.200	0.072
Walking cadence (steps/min)	G	1, 7	0.148	0.712
	P	2, 14	6.696	0.009**
	G × P	2, 14	1.078	0.367
Step length (affected) (cm)	G	1, 7	0.290	0.607
	P	2, 14	1.919	0.183
	G × P	2, 14	1.655	0.226
Step length (unaffected) (cm)	G	1, 7	0.456	0.521
	P	2, 14	4.929	0.024*
	G × P	2, 14	11.166	0.001**

TABLE III

STATISTICAL ANALYSIS RESULTS OF PAIRWISE COMPARISONS FOR ALL OUTCOME MEASURES AS A FUNCTION OF THE PERIOD FOR THE IG. $*$ P < 0.05 AND $**$ P < 0.01

Variable	Effects	Pairwise comparison Mean difference (2-1) ± Standard deviation	*p*-value
Ankle ROM (deg)	Pre^{1} vs. Post^{2}	5.127±1.582	0.043*
	Pre^{1} vs. Retention^{2}	4.970±1.343	0.023*
	Post^{1} vs. Retention^{2}	-0.157±0.933	1.000
SOT score	Pre^{1} vs. Post^{2}	13.875±3.962	0.030*
	Pre^{1} vs. Retention^{2}	15.750±4.861	0.043*
	Post^{1} vs. Retention^{2}	1.875±2.065	1.000
Walking speed (cm/s)	Pre^{1} vs. Post^{2}	13.637±2.420	0.002**
	Pre^{1} vs. Retention^{2}	14.187±4.266	0.038*
	Post^{1} vs. Retention^{2}	0.550±4.465	1.000
Walking cadence (steps/min)	Pre^{1} vs. Post^{2}	8.313±2.127	0.018*
	Pre^{1} vs. Retention^{2}	7.475±1.651	0.008**
	Post^{1} vs. Retention^{2}	-0.837±2.194	1.000
Step length (affected) (cm)	Pre^{1} vs. Post^{2}	3.888±1.500	0.107
	Pre^{1} vs. Retention^{2}	3.888±2.166	0.347
	Post^{1} vs. Retention^{2}	0±2.115	1.000
Step length (unaffected) (cm)	Pre^{1} vs. Post^{2}	7.362±1.615	0.008**
	Pre^{1} vs. Retention^{2}	8.275±2.110	0.017*
	Post^{1} vs. Retention^{2}	0.913±2.111	1.000

III. RESULTS

The independent t-test indicated no significant difference for demographic and clinical characteristics between the two groups as shown in Table I. The main effects of the groups, periods, and interactions are shown in Table II. Summaries of the results of the post hoc comparisons for the two groups are shown in Tables III and IV.

A. Ankle Range of Motion (Ankle ROM)

The repeated measures ANOVA indicated significant main effects of the period [F (2, 14) = 5.010, p = 0.023] and group × period interaction [F (2, 14) = 7.844, p = 0.005]

TABLE IV
STATISTICAL ANALYSIS RESULTS OF PAIRWISE COMPARISONS FOR ALL OUTCOME MEASURES AS A FUNCTION OF THE PERIOD FOR THE CG. $* p < 0.05$

Variable	**Effects**	**Pairwise comparison** **Mean difference (2-1) ± Standard deviation**	***p*-value**
Ankle ROM (deg)	Pre^1 vs. Post^2	1.385±1.102	0.747
	Pre^1 vs. Retention^2	1.001±1.537	1.000
	Post^1 vs. Retention^2	-0.384±0.983	1.000
SOT score	Pre^1 vs. Post^2	3.500±1.500	0.157
	Pre^1 vs. Retention^2	4.125±1.246	0.039*
	Post^1 vs. Retention^2	0.625±1.017	1.000
Walking speed (cm/s)	Pre^1 vs. Post^2	4.225±5.020	1.000
	Pre^1 vs. Retention^2	1.575±3.192	1.000
	Post^1 vs. Retention^2	-2.650±3.723	1.000
Walking cadence (steps/min)	Pre^1 vs. Post^2	3.838±3.698	1.000
	Pre^1 vs. Retention^2	2.987±2.235	0.669
	Post^1 vs. Retention^2	-0.850±2.702	1.000
Step length (affected) (cm))	Pre^1 vs. Post^2	1.400±1.737	1.000
	Pre^1 vs. Retention^2	0.175±1.473	1.000
	Post^1 vs. Retention^2	-1.225±1.365	1.000
Step length (unaffected) (cm)	Pre^1 vs. Post^2	2.600±1.960	0.679
	Pre^1 vs. Retention^2	-3.150±1.805	0.373
	Post^1 vs. Retention^2	-5.750±2.310	0.125

as shown in Table II. However, the main effects of the groups were insignificant. For the IG, post hoc pairwise comparisons indicated that ankle ROM was significantly higher at the post- and retention-assessments (78.1% and 75.7%, respectively) compared to the pre-assessment as shown in Fig. 4(a) and Table III. For the CG, the comparisons did not significantly differ between all periods as shown in Fig. 4(a) and Table IV. Furthermore, the group × period interaction of ankle ROM was significant between the pre- and post-assessment and between the pre- and retention-assessment.

B. Static/Dynamic Balance Control

The repeated measures ANOVA applied to the SOT score indicated significant main effects of the group [F (1, 7) = 8.573, $p = 0.022$], period [F (2, 14) = 10.721, $p = 0.002$], and group × period interaction [F (2, 14) = 7.813, $p = 0.005$] as shown in Table II. For the CG, post hoc analysis showed that the SOT score was significantly higher at the pre- and retention-assessments ($p = 0.014$ and $p = 0.037$, respectively) than the SOT score of the IG as shown in Fig. 4(b). For the IG, post hoc analysis showed that the SOT score was significantly higher at the post- and retention-assessments (22.1% and 25.1%, respectively) compared to the pre-assessment as shown in Fig. 4(b) and Table III. For the CG, the SOT score was significantly higher at the retention-assessment (5.1%) compared to the pre-assessment. No significant differences between the pre- and post-assessments and the post- and retention-assessments were found as shown in Fig. 4(b) and Table IV. Furthermore, the group × period interaction of the SOT score was significant between the pre- and post-assessment and between the pre- and retention-assessment.

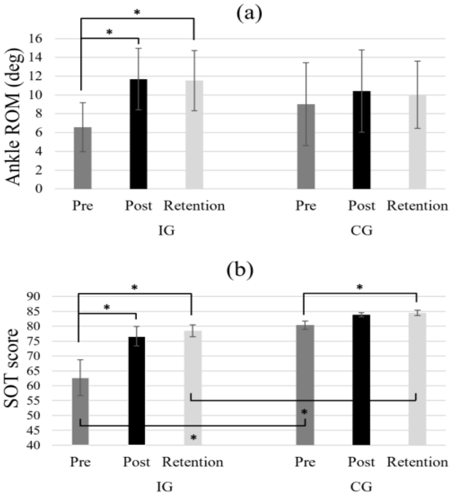

Fig. 4. Average ankle ROM [(a)] and SOT score [(b)] as a function of the group. Dark gray, black, and light gray bars indicate pre-, post-, and retention-assessment. Error bars indicate standard error of the corresponding average ($* p < 0.05$).

C. Gait Performance

The repeated measures ANOVA indicated significant main effects of the period for walking speed [F (2, 14) = 5.401, $p = 0.018$], walking cadence [F (2, 14) = 6.696, $p = 0.009$], step length for the unaffected side [F (2, 14) = 4.929, $p = 0.024$], and group × period interaction effects for step length for the unaffected side [F (2, 14) = 11.166, $p = 0.001$] as shown in Table II. There were no main effects of the group for all variables for walking speed, walking cadence, and step length for the affected and unaffected sides. There was no statistical significance for group × period interaction for walking speed, walking cadence, and step length for the affected side. For the IG only, post hoc pairwise comparisons found that walking speed, walking cadence, and step length for the unaffected side significantly increased by 24.7%, 10.0%, and 20.5%, respectively, at the post-assessment compared to the pre-assessment as shown in Fig. 5(a), (b), and (d), and that walking speed, walking cadence, and step length for the unaffected side significantly increased by 25.7%, 9.0%, and 23.0%, respectively, at the retention assessment compared to the pre-assessment as shown in the same figures. The other pairwise comparisons found no statistical significance as shown in Tables III and IV. Furthermore, the group × period interaction of step length for the unaffected side was significant between the pre- and post-assessment, between the pre- and retention-assessment, and between the post- and retention-assessment.

IV. DISCUSSION

The major findings of our assessments for the two groups of stroke survivors are as follows. For the IG, ankle ROM significantly improved at the post-assessment; carry-over effects

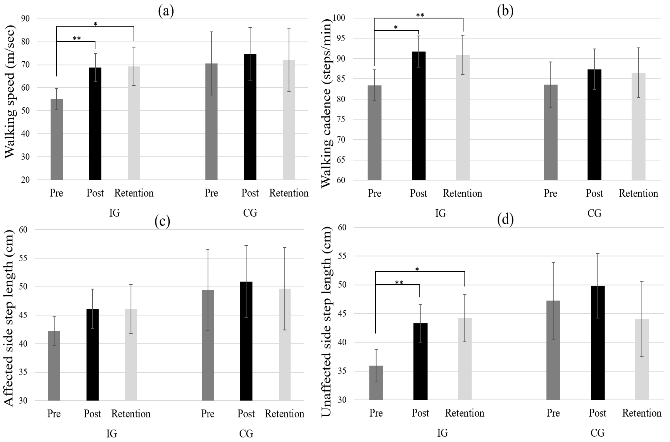

Fig. 5. Average walking speed [(a)], walking cadence [(b)], step length for the affected side [(c)], and step length for the unaffected side [(d)] as a function of the group. Dark gray, black, and light gray bars indicate pre-, post-, and retention-assessment. Error bars indicate standard error of the corresponding average (*$p < 0.05$ and ** $P < 0.01$).

were observed for balance control (SOT score) and gait performance (walking speed, walking cadence, and step length for the unaffected side); ankle ROM, balance control, and gait performance were sustained for 1 month after the completion of three and a half weeks of exercises with the MAS (see Figs. 4 and 5). For the CG, there were no significant improvements across the majority of outcome measures except for the SOT score between the pre- and retention-assessments (see Fig. 4(b)).

A. Ankle Range of Motion (Ankle ROM)

Previous studies have demonstrated that passive ankle stretching exercises with a stretching board can enhance stroke survivors' active ankle ROM and passive ankle ROM, and enhance balance and gait function [18], [41]. Chung *et al.* [23] and Zhang *et al.* [32] have found that ankle ROM significantly improved after the completion of passive ankle stretching exercises using a robotic system.

Previous studies measuring muscle activities with electromyography (EMG) found that muscle activation of the tibialis anterior correlated moderately to strongly with dorsiflexion [42], and that maintaining a standing position with dorsiflexion increased muscle activation of the tibialis anterior and surrounding muscles in healthy adults [43]. Thus, we postulated that the improved ankle ROM observed in the present study would correlate with the increased muscle activity of the tibialis anterior. Nevertheless, this assumption needs to be confirmed by measuring muscle activations around the ankle joint to identify the direct source of the beneficial effects of the passive ankle stretching exercises with the MAS on ankle ROM.

We also attributed improved ankle ROM to the fact that passive ankle stretching exercises change the biomechanical properties of muscles and tendons [24]. Multiple studies have demonstrated that higher resistance torque, increased joint stiffness, and decreased ankle ROM characterized by stroke survivors improved after completing passive stretching exercises [24], [25], [32], [44]. Therefore, we suggest that passive stretching exercises can improve extensibility and the viscoelastic properties of the muscles and tendons around the ankle joint, the number of muscle fibers, and reduce motor neuron excitability in stroke survivors [24], [26], [45], [46].

The greater improvements in ankle ROM in the IG than in the CG may be attributed to cyclic stretching (i.e., stretching gradually applied and released with multiple repetitions [47], [48]) with the MAS. Therefore, we may argue that ankle stretching exercises gradually applied and released with the MAS could increase flexibility, and decrease tensile stress and stiffness in muscles and tendons more effectively than static ankle stretching exercises with the stretching board [48].

B. Static/Dynamic Balance Control

Sustainable improvements are necessary to determine the clinical applicability of rehabilitation technology. Since maintaining stable balance can be affected by neuromuscular impairments following stroke [49], we assessed the impacts of ankle stretching exercises on static/dynamic balance control for the IG and CG. We found that only the IG significantly improved static/dynamic balance control at the post- and retention-assessments compared to the pre-assessments. We attribute these improvements to the improvements of ankle ROM because ankles play a crucial role in maintaining balance [50], [51].

Furthermore, proprioceptive information around the ankle joint resulting from sensory inputs (e.g., from cutaneous receptors, muscle-spindle receptors, and Golgi tendon organ located in muscles, tendons, and ligaments) help to maintain postural and balance control [52]. Proprioceptive information also contributes to the generation of neural signals to promote neuromuscular control during static (e.g., SOT condition 1 and 2) and dynamic (e.g., SOT condition 3 to 6) balance tasks [51], [53]. Previous studies demonstrated that ankle exercises performed while in a weight-bearing position resulted in improving proprioceptive sensation and balance control (e.g., [54]). Alterations in musculo-tendious unit stiffness and length induced by continuous stretching could improve the fidelity of ankle proprioception [55]. Therefore, we postulated that cyclic stretching involving continuous motion with the MAS improved ankle ROM and enhanced proprioceptive information around the ankle joint compared to static stretching with the stretching board.

C. Gait Performance

Impaired gait is commonly characterized by gait parameters (e.g., decreased walking speed and step length [4]) after stroke. We found that only the IG significantly improved gait performance (e.g., walking speed, walking cadence, and step length for the unaffected side) after completing ankle stretching exercises with the MAS. The improvements align with previous studies demonstrating that ankle stretching exercises for stroke patients improved impaired gait functions, e.g., Selles *et al.* [25], who found that stroke survivors showed enhancement in a comfortable walking speed after the completion of the ankle stretching exercises (3 times per week for

4 weeks). In addition, Wu *et al.* [22] have revealed that both 10-minute walking speeds and walking cadences significantly improved after stretching of the plantarflexors in stroke survivors. Plantarflexors play a critical role in generating forward propulsion while walking [9], [10], but less muscle and fascicle flexibility of plantarflexors in stroke survivors can contribute to decreased generation of forward propulsion [24], [56]. Previous studies have shown that stroke survivors generated more force outputs in impaired calf muscles after the completion of ankle stretching exercises (e.g., [24]), which can contribute to improvements in gait performance. Therefore, it can be postulated that the improved ankle ROM observed in the IG produces more power generation during trailing leg push-off as confirmed [23], [57]. Improved ankle ROM for the affected side is also likely to contribute to improvements in step length for the unaffected side because sufficient ankle ROM for the affected side can increase step length for the unaffected side during walking in stroke survivors (e.g., [57], [58]).

The improvements of gait performance (i.e., improved walking speed, walking cadence, and step length for the unaffected side) observed in the IG were retained for one month after the completion of ankle stretching exercises with the MAS have important clinical implications because sustainable improvements in gait performance is a crucial objective of stroke rehabilitation [14].

The lack of significant improvements in gait performance observed in the CG is unsurprising because there is a strong correlation between balance control and gait performance [59], [60]. Previous studies have found that enhanced balance control is the main predictor for improvements of gait performance in stroke survivors (e.g., [61]). Therefore, the results of our study align with the association between balance and gait performance in stroke survivors.

D. Potential Advantages of the Motorized Ankle Stretcher

Since repeated and high-intensity ankle stretching exercises have been generally recommended for stroke survivors [26], [62], properly designed robot-assisted therapeutic regimens tailored to stroke survivors can offer ideal exercise intensity, frequency, and duration. Potentially, robot-assisted regimens could help physical therapists assist more patients at less cost and labor [31]. For these and other reasons (e.g., cost, limited availability of physical therapists, and labor-intensive operations), there has been growing interest in developing assistive devices which provide ankle stretching exercises for stroke survivors (see [38] for review). Most existing robotic systems, however, use expensive, complex exoskeletal or parallel robot mechanisms, which make the systems inappropriate for use in clinical and home settings. The MAS has several advantages in terms of cost, flexibility, and accessibility. It also provides weight-bearing ankle stretching exercises to improve muscle tone and ankle torque compared to non-weight-bearing ankle stretching exercises (e.g., [33], [34]). The MAS can be easily configured to provide different modalities of ankle stretching exercises (e.g., passive stretching, prolonged positioning stretching, and isotonic stretching (see [27] for review).

V. CONCLUSION

This study investigated the effects of ankle stretching exercises on ankle ROM, balance control, and gait performance in stroke survivors. Those who performed the exercises with the use of a MAS significantly improved in terms of ankle ROM, balance control, and gait performance compared to those who performed them with the use of a stretching board. The improvements in the MAS users' group were retained for one month after the completion of three-and-a-half weeks of ankle stretching exercises.

This study was limited by a relatively small sample size, exclusive use of functional measurements (i.e., passive ankle ROM, ankle stiffness and spasticity, and foot proprioception), and lack of measurements for plantarflexor (e.g., gastrocnemius, soleus, and tibialis posterior) kinematics and kinetics. Despite these limitations, the results have important implications. Exercisers can use the MAS in clinical settings and in the home. Physical therapists can easily use the MAS to prescribe or adapt exercise regimens to an exerciser's specific intensity, frequency, and duration.

Future research will determine the ideal intensity, frequency, and duration of ankle stretching exercises with the MAS. Muscle activations around the ankle joint will be collected using EMG and then analyzed as a function of ankle ROM, balance control, walking, etc. In addition, the kinematics and kinetics of lower extremities during stretching exercises and evaluations of balance and gait performance will be measured and analyzed, and ankle stiffness and spasticity, and ankle and foot proprioception will be assessed.

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