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Effects of Robot-Aided Rehabilitation on Improving Ankle and Balance Performance of Stroke Survivors: A Randomized Controlled Trial

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Abstract

Background: Stroke survivors often experience abnormal posture control, which affects balance and locomotion. The ankle strategy is important in maintaining static balance. Prolonged spasticity may result in biomechanical changes at the ankle joint, which may cause balance disorders. The intelligent stretching device may decrease the stiffness of the ankle and improve balance. The purpose of this study was to investigate the effects of robot-aided ankle rehabilitation of stroke survivors with ankle spasticity and the correlations between biomechanical properties and balance in these patients.

Methods: Twenty inpatients post stroke with ankle spasticity performed 20 minutes of stretching treatment for 2 weeks. The study group used a rehabilitation robot to stretch the spastic ankle plantar flexors under intelligent control and the control group received manual stretching. Outcome measures included biomechanical, clinical evaluations and Pro-Kin balance test.

Results: After training, significant improvements were found in both groups in the active range of motion, muscle strength, Berg Balance Scale, Fugl-Meyer Motor Assessment of Lower Extremity, Postural Assessment Scale for Stroke Patients, 6-minute walk test, and Modified Barthel Index ($P<0.05$); significant decreases were found in the study group in dorsiflexion stiffness, Modified Ashworth Scale, trajectory lengths, elliptical trajectory, standard deviation medial/lateral, average speed forward/backward with eyes closed, and standard deviation forward/backward with eyes open ($P=0.001$, $P=0.037$, $P=0.028$, $P=0.019$, $P=0.016$, $P=0.001$, and $P=0.033$, respectively); dorsiflexion stiffness was positively correlated with the Pro-Kin balance test outcomes: ellipse area, trajectory length, average speed forward/backward, average speed medial/lateral with eyes open (γ=0.352, P=0.026; γ=0.522, P=0.001; γ=0.045, P=0.004; γ=0.433, P=0.005, respectively); dorsiflexion stiffness was correlated with the Modified Ashworth Scale (τ=0.265, P=0.041); the study group improved significantly more than the control group in the activities of daily living after training (P =0 .017).

Conclusions: The results suggested that robot-aided ankle rehabilitation had a positive effect on the biomechanical properties of the spastic ankle, and it may be feasible to improve balance post-stroke. Ankle dorsiflexion stiffness affected balance poststroke significantly; it may be a sensitive indicator for evaluating balance.

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Key words: Stroke; Ankle; Spasticity; Balance; Rehabilitation.

Background

Stroke survivors often experience spasticity, joint contractures, muscle weakness, and motor impairments that impede ambulation and balance and contribute directly to disabilities [1, 2]. Foot drop is a common ankle impairment that affects locomotion post-stroke [3]. Deterioration in ankle joint motion can result in clumsy gait patterns with excessive energy cost [4] and balance disorders. Previous studies have found that foot drop can be caused by impaired voluntary control, weakness of the dorsiflexor muscles or spastic plantar flexors, which can limit foot clearance during the swing phase as well as reduce loading ability during the mid-stance of gait [5].

Lack of mobilization and prolonged spasticity may be accompanied by structural changes in the muscle fibers and connective tissue, which may result in biomechanical changes at the ankle, including reduced range of motion (ROM), increased resistance and stiffness, and muscular imbalance, leading to a clinical contracture [6-9]. Recently, an intelligent stretching device was developed to decrease ankle stiffness of patients who were neurologically impaired due to stroke, spinal cord injury, multiple sclerosis, or cerebral palsy. Significant improvements were found in the ROM, maximum voluntary contraction, ankle stiffness, and comfortable walking speed [10-15].

As a crucial part of posture control, ankle strategy is important during daily ambulation and functional activities [16]. However, the correlations between the local biomechanical properties of the ankle and balance are unclear. Therefore, this study aimed to perform repeated intelligent stretching of the ankle with spasticity in patients with hemiplegia after stroke, observing the biomechanical changes in the ankle after training, and assessing static balance quantitatively using the Pro-Kin device [17], based on the assessment of postural sway using the force platform from movements of the center of pressure (CoP), and to further explore the correlations between the Pro-Kin balance test outcomes and ankle stiffness quantitatively, to determine the effect of ankle stiffness on balance.

METHODS

Subjects

Patients with subacute stroke hospitalized in the Beijing Tsinghua Chang Gung Hospital between March 2019 and August 2019 were recruited. The inclusion criteria were: (1) ages between 18 and 75 years; (2) first-ever stroke with less than 6 months duration of spasticity of the affected ankle (Modified Ashworth Scale, MAS: 1~2); (3) medically stable; (4) ability to stand independently without aids for at least 1 minute; and (5) ability to perform the experimental treatment independently. Exclusion criteria were communication problems, dementia based on clinical diagnosis, comorbidities affecting motor performance such as orthopedic, arthritic, inflammatory conditions that could influence balance, and limited ankle movement. Finally, 20 stroke survivors with impaired ankle motor function participated in this study.

Experimental setup

An ankle rehabilitation robot (Beijing LTK Science and Technology Co., Ltd) was used for intervention and outcome evaluations [18]. The leg of the subject was strapped to a leg support with the knee at 10° flexion and the foot was strapped onto a footplate with ankle dorsiflexion (DF) at 0°. The footplate was fixed to the motor shaft, and a torque sensor was aligned with the motor shaft to measure the ankle joint torque (Fig. 1).

Fig. 1 A patient seated in the ankle rehabilitation robot device.

Stretching protocol

Patients in the Department of Rehabilitation Medicine in the hospital were randomly assigned to the study (n=10) or control (n=10) group. Patients in the study group had 10 sessions (five times a week over 2 weeks). Each session comprised 20 minutes training by stretching the ankles with spasticity under intelligent control. Training for the control group involved manual stretching of the plantar flexors (five times a week over 2 weeks, 20 minutes/session). During the 2-week period, both groups continued active movement exercises for ankle mobility and strength. Patient allocation was made by an investigator not involved in the assessments and training, based on a computer-generated random number. The ankle rehabilitation robot was driven by a servomotor controlled by a digital signal processor [10]. Briefly, the stretching velocity was inversely proportional to the joint resistance torque. Typical values were 30°/s peak stretching velocity, 10 to 40 Nm peak resistance torque in dorsiflexion, 5 to 10 Nm peak resistance torque in plantarflexion, and a 5-s holding period at extreme dorsiflexion [11]. An experienced physical therapist adjusted the peak resistance torque for each session based on manual stretching and feedback from the subject during the stretching.

Data assessed

Subjects were tested before and after the training period by a blinded investigator. Biomechanical, clinical evaluations and the Pro-Kin balance test (PK252, TecnoBody, Italy) were conducted. All assessment sessions were performed at the same time of day and in the same order.

Biomechanical evaluations

Evaluations included the passive and active ranges of motion (PROM, AROM),, dorsiflexor and plantarflexor muscle strength, and DF and plantarflexion (PF) stiffness. ROM and muscle strength were measured using the HogganMicroFET3 portable device (Hoggan Health Industries, Inc. Salt Lake City, USA). The measuring range of ROM was 0–180° with an accuracy of 1°; the measuring range of muscle strength was 3.6–890 N with an accuracy of 0.01 N (Fig. 2). The stiffness measured in DF or PF passive movement was assessed as $K=\Delta T/\Delta\theta$, where K (Nm/deg) was the quasi-static stiffness and ΔT was the passive torque increment during a certain amount of ankle angular movement ($\Delta\theta$). As

Δθ becomes infinitely small, the quasi-static stiffness approaches the slope of a tangential line of the torque-angle curve at a specific ankle position [10] [19, 20]. The peak stretching velocity in this study was set at 5°/s to avoid inducing reflex responses [21]. Quasi-static stiffness of the ankle plantar flexor (stiffness measured in DF direction movement, DF stiffness) was evaluated at 10° of DF and that of the ankle dorsiflexor (stiffness measured in PF direction movement, PF stiffness) at 30° of PF. Three trials were conducted and the averages were taken to be AROM, PROM, muscle strength, and stiffness (K).

(a) (b)

Fig. 2 ROM (a) and muscle strength (b) measured by Hoggan MicroFET3 portable device.

Clinical evaluations

Each subject completed the following functional assessments during clinical evaluation sessions. MAS (0–4 points) [22] was used to measure the calf muscle hypertonia. Fugl-Meyer Motor Assessment of Lower Extremity (FM-LE) [23] (0–34 points) was used to evaluate the sensorimotor function of the lower limbs. The Berg Balance Scale (BBS) [24] (0–56 points) was used to evaluate the balance function. The 6-minute walk test (6MWT) [25] was used to determine walking ability. The Postural Assessment Scale for Stroke Patients (PASS) [26] (0–36 points) was used to evaluate the ability to control posture. The

Modified Barthel Index (MBI) [27] (0–100 points) was used to measure the activities of daily living (ADL).

Pro-Kin balance evaluations

This study also used the Pro-Kin system (PK252, TecnoBody, Italy) to assess balance function, which was based on the assessment of postural sway using the force platform from movements of the center of pressure (CoP) [28-30] (Fig. 3). Subjects stood on the platform comfortably, looking straight ahead at a screen and keeping arms at their sides during the stances, with eyes focused on a stationary target. Each participant performed two standing tests, with opened eyes (OE) and closed eyes (CE), each test lasting 30s, using a sampling frequency of 20 Hz. Postural sway was determined using six different outcome variables: trajectory lengths (measured in mm), elliptical trajectory (measured in mm^2), standard deviation medial/lateral (M/L SD), standard deviation forward/backward (F/B SD), average speed medial/lateral (M/L AS measured in m/s), and average speed forward/backward (F/B AS measured in m/s). The trajectory lengths referred to the length of the trajectory of the pressure center; the greater the length, the poorer the balance function the patient displayed. Elliptical trajectory referred to the area surrounded by the trajectory of the center of the body pressure; the larger the area, the poorer the balance function the patient demonstrated. An increase in CoP in either the forward/backward or medial/lateral direction was indicative of postural disturbance, including SD and AS. Smaller values of the six parameters indicated the patient had a better balance function [31].

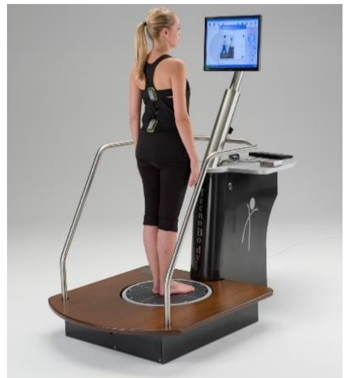


Fig. 3 Static Balance Assessed by the Pro-Kin System

Statistical analyses

Differences in general characteristics of the subjects between the two groups were assessed using the Mann-Whitney U test or Fisher's exact test. For all outcome variables, the group mean and standard deviation at pre- and post-training were calculated. The values were compared between the groups using the two-way repeated ANOVA. Post-hoc paired sample t-test with Bonferroni correction within the study and control groups was performed. We used Pearson's coefficient to examine the correlation between stiffness (K) and the Pro-Kin system results, and the Kendall rank correlation coefficient (τ) for the correlation between MAS and K [32]. A significance level of $p \leq 0.05$ was set for two-way repeated ANOVA models and correlation tests. All statistical tests were analyzed using IBM SPSS Statistics for Windows, version 21.0. (IBM Corporation, Armonk, NY, USA).

Results

Baseline characteristic of subjects and compliance

Characteristics of the subjects are described in Table 1. All subjects completed the full 2-week treatment. There were no significant differences in age, duration post stroke, sex, side of lesion, height, weight, or BMI (Body Mass Index) between the two groups (Table 1).

Table 1. Baseline Characteristics of the Participants

Parameters	Study group (n=10)	Control group (n=10)	P Value
Age（year）	61.90 ± 9.62	60.00 ± 6.62	0.613
duration post stroke	54.20 ± 33.85	58.10 ± 50.20	0.841
Sex (M/F)	9/1	9/1	
Cerebral infarction/cerebral hemorrhage (case)	10/0	10/0	
Side of lesion (left/right, case)	7/3	7/3	
Height（m）	1.68 ± 0.05	1.69 ± 0.04	0.573
Weight (kg)	74.70 ± 9.71	70.40 ± 5.40	0.237
BMI (kg/m^2)	26.33 ± 3.65	24.45 ± 1.72	0.158

P-values indicate the results of Mann-Whitney U Test for age and duration post stroke, and of Fisher's exact test for all the other variables. Values are mean ± standard deviation, or number. BMI, Body Mass Index; M, male; F, female

Biomechanical evaluations: PROM, AROM, muscle strength and joint stiffness

Before training there were no significant differences in PROM, AROM, muscle strength, or DF and PF stiffness between the two groups. The DF AROM, PF AROM, DF muscle strength, and PF muscle strength increased significantly after the 2-week training period in the control group (P=0.032; P=0.001; P=0.011; P<0.0001, respectively). The four parameters of biomechanical properties showed similar changes in the control group as in the treatment group (P=0.001; P=0.002; P=0.007; P=0.001, respectively). In addition, significant decreases in DF stiffness were found for subjects in the study group (P=0.001) but not in the control group. No significant differences in biomechanics were found between the two groups after training (P>0.05) (Table 2, Fig. 4).

Table 2. Biomechanical Properties at pre- and post-treatment between two groups

	Study group		Control group	
Variable	Pre-training	Post-training	Pre-training	Post-training
DF AROM (°)	7.60 ± 5.62	10.90 ± 4.15*	8.70 ± 6.45	10.60 ± 5.85*
DF PROM (°)	15.50 ± 2.17	16.70 ± 1.42	17.00 ± 1.15	17.20 ± 1.23
PF AROM (°)	19.60 ± 10.97	23.10 ± 10.13*	18.00 ± 16.52	22.20 ± 15.84*
PF PROM (°)	38.30 ± 4.62	39.60 ± 4.01	39.50 ± 4.34	40.20 ± 4.94
DF Strength (N)	102.50 ± 44.54	132.82 ± 43.44*	101.4 ± 59.71	123.80 ± 58.55*
PF Strength (N)	144.80 ± 36.29	167.68 ± 29.31*	122.10 ± 47.45	160.53 ± 58.86*
DF Stiffness (Nm/deg)	1.62 ± 0.24	1.19 ± 0.24*	1.32 ± 0.41	1.10 ± 0.42
PF Stiffness (Nm/deg)	0.21 ± 0.04	0.19 ± 0.03	0.21 ± 0.07	0.24 ± 0.09

Values are mean ± standard deviation. * $p < .05$ for Pre vs Post, § $p < .05$ for Study group vs Control group Post-training. The change of biomechanical properties over time within each group was evaluated using Post-hoc paired sample t-test with Bonferroni correction. The values were compared between the groups using the two-way repeated ANOVA. DF or PF stiffness is stiffness measured in dorsiflexion or plantarflexion passive movement.

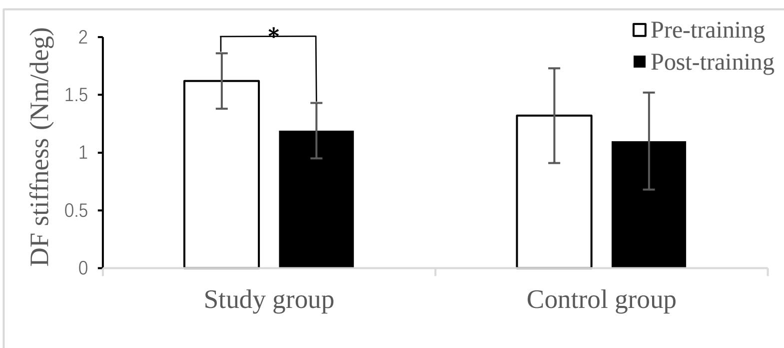


Fig. 4 DF stiffness before and after 2 weeks of training in the two groups. *P<.05.

Clinical evaluations

There was no significant difference in MAS, FM-LE, BBS, PASS, 6MWT, or MBI before training between the two groups. The FM-LE, BBS, PASS, 6MWT, and MBI increased significantly after the 2-week training period in the control group (P=0.006; P=0.004; P=0.002; P=0.018; P=0.029, respectively). We also found significant improvement in FM-LE, BBS, PASS, 6MWT, and MBI in the study group (P=0.001; P=0.037; P=0.009; P=0.028; P=0.001, respectively). In addition, significant decreases were found in MAS for subjects in the study group (P=0.037) but not in the control group. Subjects in the study group improved significantly more than those in the control group in the activities of daily living (ADL) by MBI after the 2-week training (P =0.017) (Table 3, Fig. 5, 6).

Table 3. Clinical evaluations at pre- and post-treatment between two groups

	Study group		Control group	
Variable	Pre-training	Post-training	Pre-training	Post-training
MAS	1.30 ± 0.48	$0.90 \pm 0.57^{*}$	1.10 ± 0.32	1.00 ± 0.47
FM-LE	26.50 ± 5.36	$29.30 \pm 4.42^{*}$	24.80 ± 7.25	$27.60 \pm 6.31^{*}$
BBS	41.40 ± 13.74	$45.00 \pm 13.87^{*}$	43.40 ± 10.23	$46.70 \pm 9.93^{*}$
PASS	30.10 ± 4.28	$31.40 \pm 3.50^{*}$	29.90 ± 3.96	$31.60 \pm 3.72^{*}$
6MWT	96.80 ± 99.49	$131.40 \pm 95.99^{*}$	131.30 ± 117.57	$170.20 \pm 129.28^{*}$
MBI	59.50 ± 15.89	$75.00 \pm 14.14^{*}$	75.50 ± 19.21	$80.00 \pm 17.95^{*§}$

Values are mean ± standard deviation. * $p < .05$ for Pre vs Post, § $p < .05$ for Study group vs Control group Post-training. The change of Clinical evaluations over time within each group was evaluated using Post-hoc paired sample t-test with Bonferroni correction. The values were compared between the groups using the two-way repeated ANOVA. MAS Modified Ashworth Scale, FM-LE Fugl-Meyer Motor Assessment of Lower Extremity, BBS Berg Balance Scale, PASS Postural Assessment Scale for Stroke Patients, 6 MWT 6-minute walk test, MBI Modified Barthel Index.

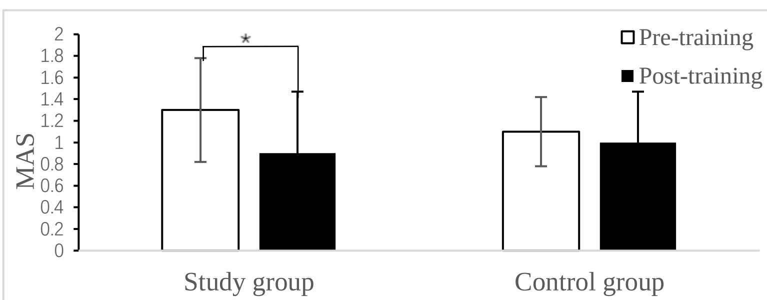


Fig.5 MAS before and after 2 weeks of training in the two groups. *P<.05.

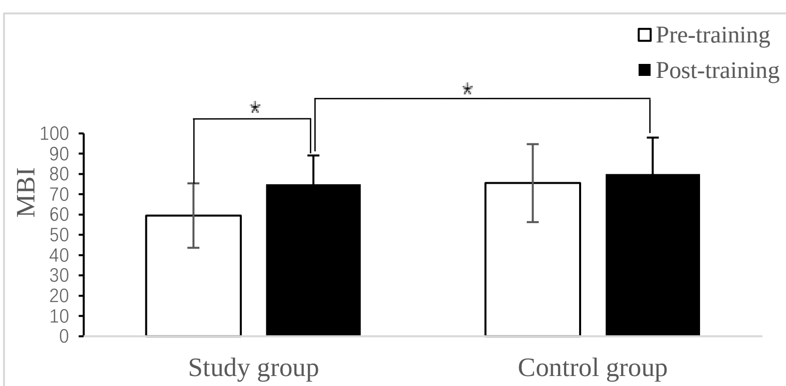


Fig.6 MBI before and after 2 weeks of training in the two groups. *P<.05.

Pro-Kin balance test outcomes

There was no significant difference between the two groups in ellipse area, trajectory length, F/B SD, L/M SD, F/B AS, or L/M AS with opened and closed eyes before training. The ellipse area, trajectory length, L/M SD, and F/B AS with closed eyes and F/B SD with opened eyes decreased significantly after the 2-week training period in the study group (P=0.028; P=0.019; P=0.016; P=0.001; P=0.033, respectively). We found no significant change in the control group. No significant difference in the Pro-Kin balance test outcomes was found between the two groups after training (P>0.05) (Table 4). Examples of the trajectory of the CoP of two groups are shown in Fig. 7, 8. It can be noticed that the participant S09 attained a better balance function after training than participant C07 significantly.

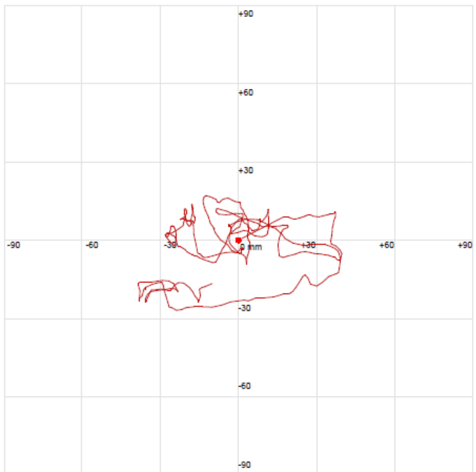
Table 4. Pro-Kin balance test outcome at pre- and post-training between two groups

	Study group		Control group	
Variable	Pre-training	Post-training	Pre-training	Post-training
Eyes Closed				
Ellipse Area mm^2	1396.10 ± 1085.48	$847.70 \pm 486.15^*$	2431.50 ± 2569.09	1371.00 ± 1236.41
Trajectory Length mm	962.40 ± 344.94	$820.80 \pm 280.43^*$	1141.30 ± 613.22	918.00 ± 522.08
F/B SD	7.40 ± 1.90	6.80 ± 2.53	10.20 ± 4.76	7.60 ± 2.72
L/M SD	10.10±5.34	$6.10 \pm 2.77^*$	10.50 ± 6.00	9.10 ± 4.79
F/B AS mm/sec	22.30 ± 8.37	$18.60 \pm 7.11^*$	23.50 ± 14.87	19.30 ± 14.12
L/M AS mm/sec	18.90 ± 7.94	17.50 ± 7.86	19.50 ± 13.30	15.40 ± 11.11
Eyes Open				
Ellipse Area mm^2	755.50 ± 659.29	518.90 ± 224.25	713.20 ± 450.40	533.40 ± 201.92
Trajectory Length mm	585.30 ± 188.54	458.70 ± 122.65	539.30 ± 182.93	459.40 ± 126.06
F/B SD	5.80 ± 2.15	$4.50 \pm 0.85^*$	5.80 ± 1.75	5.10 ± 0.88
L/M SD	7.10 ± 4.38	6.10 ± 1.73	6.10 ± 2.08	5.90 ± 2.13
F/B AS mm/sec	13.60 ± 5.46	10.80 ± 2.62	11.30 ± 5.06	10.20 ± 3.97
L/M AS mm/sec	11.00 ± 2.91	9.10 ± 4.31	11.10 ± 4.12	9.00 ± 2.00

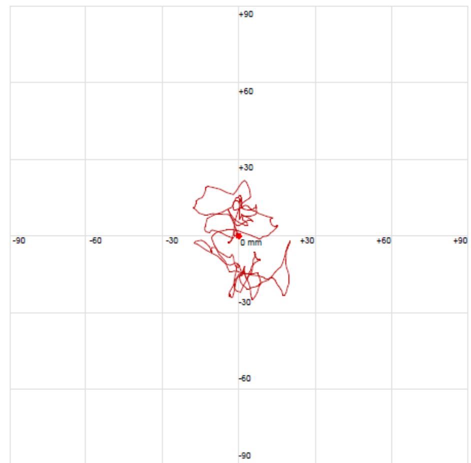
Values are mean ± standard deviation. * $p < .05$ for Pre vs Post, § $p < .05$ for Study group vs Control group Post-training. The change of Pro-Kin balance test outcome over time within each group was evaluated using Post-hoc paired sample t-test with Bonferroni correction. The values were compared between the groups using the two-way repeated ANOVA. AS Average speed, Forward/Backward F/B, Medial/Lateral direction M/L.

Subject S09-Study Group

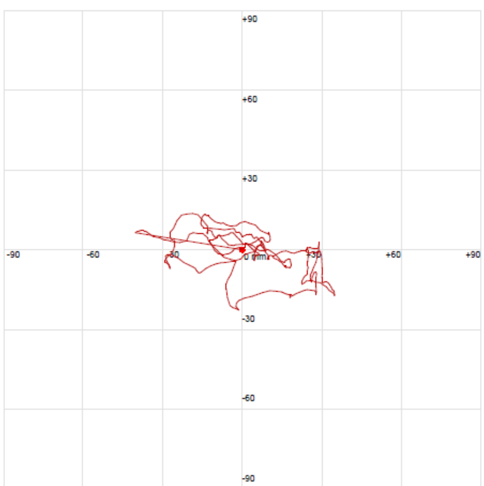
A. Trajectory of the CoP Pre-training (CE)



B. Trajectory of the CoP Post-training (CE)



C. Trajectory of the CoP Pre-training (OE)



D. Trajectory of the CoP Post-training (OE)

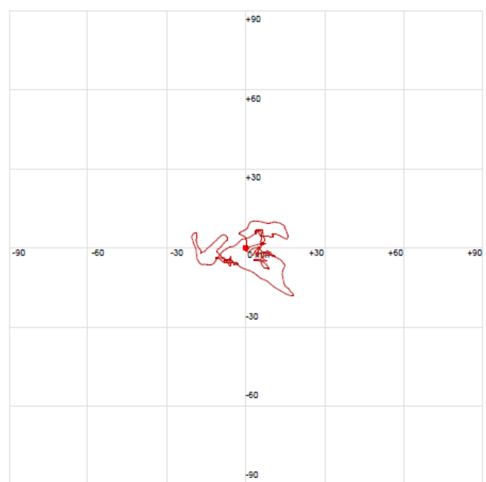
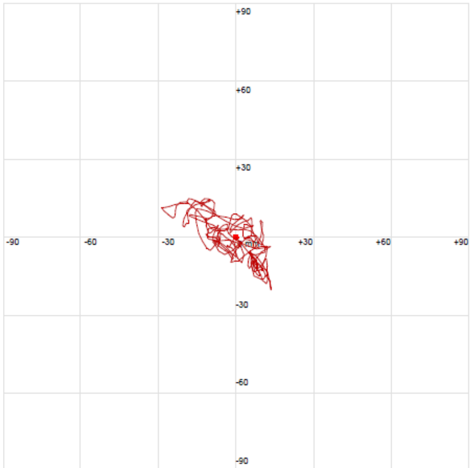
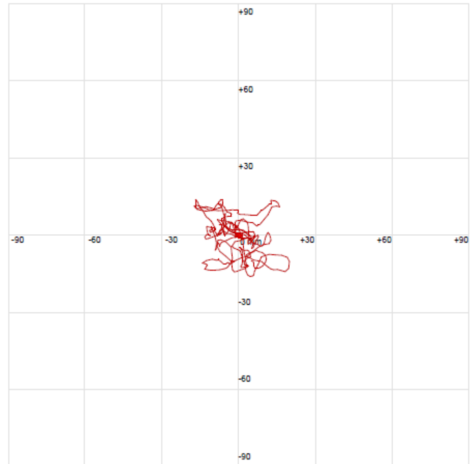


Fig 7. Example of the trajectory of the center of pressure (CoP) of Pre-training (a, c) and Post-training (b, d) from the Study Group with opened eyes (OE) and closed eyes (CE).

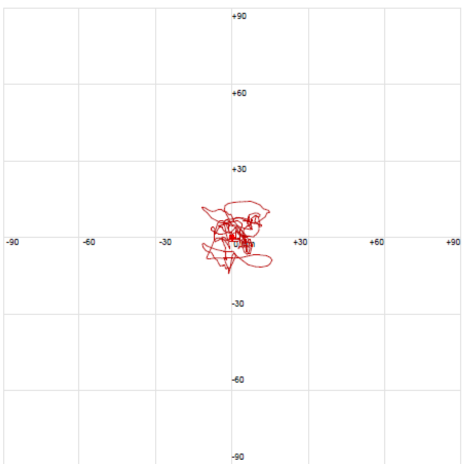
Subject C07-Control Group

A. Trajectory of the CoP Pre-training (CE) **B. Trajectory of the CoP Post-training (CE)**





C. Trajectory of the CoP Pre-training (OE) **D. Trajectory of the CoP Post-training (OE)**



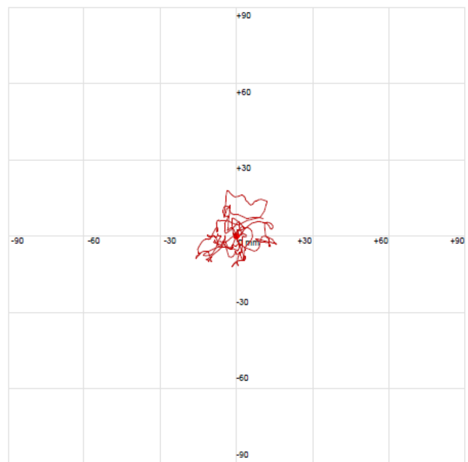


Fig 8. Example of the trajectory of the center of pressure (CoP) of Pre-training (a, c) and Post-training (b, d) from the Control Group with opened eyes (OE) and closed eyes (CE).

Correlations between stiffness of the ankle and the balance function

The DF stiffness was significantly correlated with the outcomes of the Pro-kin balance test with opened eyes, including the ellipse area, trajectory length, F/B AS, M/L AS (γ=0.352, P=0.026; γ=0.522, P=0.001; γ=0.045, P=0.004 ; γ=0.433, P=0.005, respectively). The DF stiffness was also significantly correlated with MAS (τ=0.265, P=0.041) (Table 5).

Table 5 Correlations Between stiffness and Pro-Kin balance test outcome when open eyes

	DF stiffness	P value	PF stiffness	P value
MAS	0.265	0.041*	−0.154	0.344
Ellipse Area	0.352	0.026*	−0.217	0.179
Trajectory Length	0.522	0.001*	−0.312	0.050
F/B SD	0.285	0.075	−0.158	0.331
M/L SD	0.277	0.084	−0.263	0.101
F/B AS	0.450	0.004*	−0.283	0.077
M/L AS	0.433	0.005*	−0.252	0.116

Pearson's coefficient (γ)was used to estimate the correlation between stiffness (K) and the Pro-Kin system results, and the Kendall rank correlation coefficient (τ) was used to estimate the correlation between stiffness (K) and MAS. Values are γ or τ. *significance level of $p \leqslant 0.05$ was set for correlation tests.

Discussion

The main findings of our randomized controlled pilot study were that both conventional manual and robotic intelligent stretching of spastic ankles could improve the biomechanical properties of the ankle joints and motor function. For the study group, the spasticity of the ankle decreased more as evaluated by DF stiffness and MAS, and the balance function improved more as evaluated by the Pro-Kin balance test compared with the control group. This study found that robot-aided rehabilitation of the ankle could invoke more benefits in joints with impaired biomechanical properties than the methods used in the control group by decreasing stiffness of the spastic ankle to improve balance and activities of daily living. The stiffness of dorsiflexion as a crucial biomechanical property of the local ankle joint influenced the overall balance in stroke deeply; it may be a sensitive indicator for evaluating the ability to balance. All subjects completed the intervention successfully, and there were no adverse effects reported for this research.

A. Biomechanical properties of the spastic ankle

Several studies have reported the positive effects of stretching subjects with joint spasticity and/or contracture by decreasing muscle tone, improving soft-tissue extensibility, and increasing ankle ROM [33-39]. Manual stretching by moving the spastic ankle through its ROM requires labor-intensive efforts, and the outcome is dependent on the experience of the therapist, which limits its availability. Thus, external devices [40, 41] and robotic systems [11, 36, 42-44] have served as an alternative rehabilitation tool for stretching of the ankles and training for functional movement. Specifically, robot-aided rehabilitation of the ankle has been used effectively in treating ankle contracture and/or spasticity, and previous studies indicated that this intervention reduced ankle joint resistance torque and stiffness, increased ROM [10], and improved balance and gait [34, 35] in neurologically impaired patients. Robotic intervention in the form of intelligent stretching and active movement training has been studied in children with cerebral palsy and showed significant improvement in 12 children with CP in terms of improved passive and active ranges of motion, selective motor control, and mobility functions after 18 sessions of training (three sessions/week for 6 weeks) [12]. Waldman et al investigated the effects of the robotic rehabilitation of the ankle in stroke with ankle impairment, and the results showed subjects in the robot group improved significantly more in dorsiflexion PROM, dorsiflexion strength, and balance and walking function, while the spasticity measured by the Modified Ashworth Scale was reduced more than that in the control group [45]. Forrester et al [46, 47] conducted similar studies, and the results suggested that robotic rehabilitation of the ankle was effective in improving balance, motor function, and mobility poststroke. In this study, to forcefully and safely stretch the ankle of a subject with spasticity to its extreme positions, we used an intelligent stretching device that stretched the joint with quantitative feedback control of the resistance torque and stretching velocity. The stretching device was driven by a servomotor controlled by a digital signal processor (DSP) [18]. The exact rules of the DSP-controlled motion have been described elsewhere [10]. By using this control strategy, the stretching device moved quickly in the middle (non-spastic) ROM and slowed in the stiffer part of the ROM, while never exceeding preset stretching torques. This study demonstrated that improvement associated with the intelligent stretching of the spastic ankles post-stroke was consistent with previous research, and resulted in increased ROM and muscle strength, decreased ankle stiffness, and improved balance and mobility function. This type of high intensity, repetitive and efficient stretching can be more labor-saving and readily available to patients without the need of a skilled therapist. Furthermore, in this study, a significant correlation (τ=0.265, P=0.041) was observed between MAS and DF stiffness, which is consistent with previous research. This measure of stiffness may potentially be used to obtain more accurate and quantitative evaluation of spastic hypertonia in future [11].

B. Balance control

Postural stability, often defined as balance, is the ability of the body to maintain its center of mass over the base of support [48], and it plays an important role in the recovery of motor function in patients with hemiplegia. Three kinds of strategy are involved in postural control in humans: ankle strategy, hip strategy, and stride strategy [28, 29]. The ankle strategy refers to the body's center of gravity rotating or swinging around the ankle joint in a pendulum movement, which is the main strategy in normal people for maintaining balance when the support surface is firm and the perturbations are small [24, 49], while the hip strategy is mainly activated when the range of body sway is large. The most important roles of the ankle joints and the feet are in controlling body sway and forward movements of the lower extremities, and these roles require a sufficient range of motion, muscle strength, and proprioceptive sense in the ankle joints [50]. The ankle strategy is damaged partially after stroke creating muscular imbalance surrounding the ankle, increased joint stiffness, decreased proprioception of the ankle, and wrong central integration, which causes functional instability and/or imbalance [51].

At present, various therapeutic methods have been used to improve balance post-stroke, such as task-related training assisted-robot walking, virtual reality rehabilitation, core strength exercises [7], visual feedback training etc [52, 53]. These methods of rehabilitation treat the patient as a whole, aiming to improve the posture control of the trunk and lower limbs. In our study, we focused on the reapplication of the ankle strategy to improve balance via robot-aided rehabilitation of the ankle. It forcefully, safely, and repeatedly stretched the ankle to its extreme positions resulting in structural changes in the viscoelastic properties of the connective tissues, thereby reducing ankle stiffness and increasing sensory inputs around the ankle joints (including cutaneous receptors, muscle-spindle receptors, and Golgi tendon organs located in the muscles, tendons, and ligaments). The patients were asked to stare at the display screen where an amplified and lateral "ankle joint" image was shown as stretching the ankle from dorsiflexion to plantarflexion, which was a real-time visual feedback integrating proprioception with the environment, promoting neuromuscular control during training [54, 55].

C. Pro-Kin balance test

To measure the ability to balance quantitatively, the Pro-Kin is a useful piece of equipment that has demonstrated reliability with the capability to feasibly generate instantaneous data regarding CoP, including the perimeter, ellipse, and movement in both the forward/backward and medial/lateral directions [31]. This balance test system only requires patients to have a certain ability to sit or stand, and it can find subtle balance differences more comprehensively, making up for the measurement errors caused by subjective factors in the balance scales assessment [56]. In this study, the Pro-Kin was used to quantitatively evaluate the standing static balance of patients before and after training, excluding the influences of the hip strategy and stride strategy, and explore the role of ankle strategy in balance more accurately [57, 58]. The results showed that, after the intelligent stretching training of the ankle joint, trajectory lengths, elliptical trajectory, SD M/L, AS F/B with closed eyes, and SD F/B with opened eyes decreased significantly, but there were no significant decreases in the control group, which confirmed that robot-aided rehabilitation of the ankle is of great significance in the implementation of ankle strategy for the reestablishment of the correct depiction of the proprioceptive and muscular motor sensations. However, the balance scales failed to reflect the subtle differences in balance function after training between the two groups quantitatively. Quantitative results of the Pro-Kin balance test have the potential to increase the sensitivity of measures to guide treatment approaches and track patient progress over time.

Furthermore, we found that there were no significant improvements in trajectory lengths, elliptical trajectory, SD M/L, or AS M/L with opened eyes in the study group after training. As an explanation, we consider the following factors. First, on the stable support surface, the weight effects of proprioception, vestibule, and vision on the balance were 70%, 20%, and 10%, respectively [59], which showed that proprioception was the most important factor in maintaining balance when standing and walking on a flat surface. Visual compensation is extremely important when proprioception is destroyed post stroke [60]. However, it is more difficult to maintain balance while conducting the Pro-Kin test with eyes closed as the visual compensation is impaired, so significant improvements were easier to find with eyes closed but not open [61]. Secondly, when standing normally on a flat and solid surface, the limit of stability (LOS) was 8° in the medial, lateral, forward directions and 4.5° in the backward direction [62]. It was more difficult to maintain balance in the forward/backward direction, so the SD and AS of F/B may reflect the changes in balance more sensitively. In our study, the SD and AS of F/B deceased with open eyes after intelligent stretching training, which implied sensitive feed-back and feed-forward control mechanisms were improved [63].

D. Correlations between DF stiffness and balance

There has been no study that quantitatively analyzed the impact of local biomechanical properties of the ankle on the overall balance function. This study further explored the correlation between ankle stiffness and the Pro-Kin balance test outcomes with opened eyes. The findings showed that the stiffness of dorsiflexion was positively related to trajectory length, elliptical trajectory, and average velocity M/L and F/B with opened eyes, and trajectory length was strongly positively related to the stiffness of dorsiflexion (γ= 0.522, P =0.001), which meant that greater DF stiffness resulted in a worse balance function. But there was no significant correlation between PF stiffness and the Pro-Kin balance test outcomes, suggesting that DF stiffness was an important factor affecting the balance function, while PF stiffness was not, but the mechanism was not clear. We assumed that the decreased DF stiffness might activate the muscles around the ankles (especially the ankle dorsal flexor muscle) and increase the proprioceptive sense inputs and ROM of the ankle joint, so that the ability to appropriately control balance during sway was improved through better coordination and mobilization of the senses and muscle functions of the ankle after intelligent stretching.

Study limitations

This study had some limitations. First, a small number of subjects were enrolled; further studies should increase the number of subjects to increase the power of the study. Second, no significant differences in walking function between the two kinds of intervention were found. This might be because the training frequency, intensity, and total repetitions were not optimal, or the long-term effects of intelligent stretching training were unknown, so further follow-up is necessary to explore the effects on walking function, and further studies should focus on exploring the optimal training protocol. Moreover, the patients in our study were adults with subacute stroke, and thus the results do not apply to patients with acute and chronic stroke. Hence, the possible effects of the intervention on patients with acute and chronic stroke require further investigation.

Conclusion

The robot-aided rehabilitation of the ankles provided well-controlled passive stretching to stroke survivors with ankle impairments, and benefits included improvements in biomechanics, spasticity, balance, motor function, and ADL post-stroke. Findings in this study suggested that robot-aided rehabilitation may be a beneficial addition to rehabilitation programs. As an important part of posture control, ankle strategy was of great significance for improving the overall balance. In particular, stiffness of dorsiflexion was an important factor affecting the balance. As a local biomechanical property of the ankle, it may be a sensitive indicator for evaluating the balance function after rehabilitation and predicting the risk of falls in the future.

Abbreviations

ROM: Range of Motion; CoP: Center of Pressure; MAS: Modified Ashworth Scale; DF dorsiflexion; PF: plantarflexion; FM-LE: Fugl-Meyer Motor Assessment of Lower

Extremity; BBS: Berg Balance Scale; 6MWT: 6-minute walk test; PASS: Postural Assessment Scale for Stroke Patients; MBI: Modified Barthel Index; ADL: Activities of daily living; OE: Opened eyes; CE: Closed eyes; SD: Standard deviation; AS: Average speed; M/L: Medial/Lateral; F/B: Forward/Backward; BMI: Body Mass Index; M: male; F: female; DSP: Digital signal processor.

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Authors' contributions

YP and LZ contributed to the study design, analysis and interpretation of data and revisions to the manuscript. QW contributed to the analysis and interpretation of data. XZ contributed to the study design, data collection, analysis and interpretation of data and drafting the manuscript. Data collection was performed by XZ, XL and QX. YZ and SF performed experiments. All authors read and approved the manuscript submitted and agree to be accountable for all aspects of the work.

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author upon appropriate request.

Ethics approval and consent to participate

All protocols were reviewed and approved by the Beijing Tsinghua Chang Gung Hospital Medical Ethics (18172-0-01) according to the Declaration of Helsinki. Informed written consent was obtained from each subject in this study. This study is registered at http://www.chictr.org.cn under the study identifier ChiCTR2000030108.

Consent for publication

Consent for publication were included as part of informed consent.

Competing interests

Li-Qun Zhang holds an equity position in Beijing LTK Science and Technology Co., which made the ankle rehabilitation robot used in this study. The other authors declare that they have no competing interests.

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