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

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Research

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Abstract

Background: Stroke survivors with impaired ankle control due to stiff plantar flexors often experience abnormal posture control, which affects balance and locomotion. Forceful and safe stretching under intelligent control may decrease ankle stiffness and improve balance. The purpose of this study was to investigate the effects of robot-aided ankle rehabilitation on stroke survivors with ankle spasticity and the correlations between biomechanical properties and balance in these participants.

Methods: Twenty patients poststroke with ankle spasticity received 20 minutes of stretching treatment daily over 2 weeks. The study group used a robot-aided ankle rehabilitation and the control group received manual stretching. Outcome measures included biomechanical, clinical evaluations, and the Pro-Kin balance test.

Results: The study group significantly improved in joint stiffness and range of motion of dorsiflexion, Modified Ashworth Scale (MAS), trajectory lengths, elliptical trajectory, standard deviation medial/lateral, average speed forward/backward with eyes closed, and standard deviation forward/backward with eyes open in the Pro-Kin test (P<.05), but no significant changes were found in the control group in above indexes; significant decreases were found in the control group in trajectory length with eyes open (P<.05); dorsiflexion stiffness was positively correlated with the Pro-Kin test outcomes with eyes open and the MAS; no between-group significant changes were found except the activities of daily living after training (P<.05).

Conclusions: Ankle stiffness may affect balance poststroke significantly. The robot-aided ankle rehabilitation improved biomechanical properties of the spastic ankle including stiffness, and it may help improve balance post-stroke.

Trial registration: www.chictr.org.cn ChiCTR2000030108. Registered 23 February 2020. Retrospectively registered.

Introduction

Maintaining stable balance control is important for activities of daily living [1,2]. The ankle control mechanism is one of the most important components for balance control while standing and walking. Coordinated ankle movements contributed by plantar flexors and dorsiflexors are crucial in maintaining static balance [3,4]. The balance control of most stroke survivors is often impaired because of muscle weakness, sensory loss, and/or motor dysfunction [1,2,4]. In particular, stiff plantar flexors and weak dorsiflexors on the affected side increase the risk of postural imbalance in stroke survivors [5]. Lack of mobilization and prolonged spasticity post-stroke may be accompanied by structural changes of muscle fibers and connective tissue, which may result in a reduction in ankle joint range of motion (ROM) and a clinical contracture [6-8]. Limited ankle ROM in most stroke survivors impairs balance control, which is a major risk factor for falls [9,10]. Therefore, alleviating ankle muscle stiffness and improving the muscles’
soft-tissue extensibility and viscoelastic properties are important rehabilitation goals for stroke survivors in reestablishing balance control [11].

The most common therapeutic regimens prescribed are passive ankle stretching exercises [12,13]. Passive ankle stretching can be manually applied by physical therapists or by using a stretching board [13,14], or by robotic systems [15,16]. Cost, labor-intensive manual provision, availability of physical therapists, and survivors’ limited access to clinical facilities have restricted stroke survivors from receiving clinical therapeutic regimens, and in practice, there are various individual difference factors in the actual effect of manual stretching, such as manual feeling, manual stretching intensity, and consistency, etc. Recently, an intelligent stretching device was developed to decrease ankle stiffness of patients with neurological impairment 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 [16-20]. The robot adaptive stretching maybe a quantitative stretching supplement solution.

As a crucial part of posture control, ankle strategy is key during daily ambulation and functional activities [21]. However, the correlations between the local biomechanical properties of the ankle and balance are unclear. Therefore, this study aimed to perform adaptive intelligent stretching of the ankle with spasticity in stroke survivors with hemiplegia, observing the biomechanical changes in the ankle after training, and assessing balance using the Pro-Kin device [22], based on the assessment of postural sway using the force platform from movements of the center of pressure (CoP), and to further investigate the correlations between the Pro-Kin measures and ankle stiffness, to determine the effect of ankle stiffness on balance.

**Methods**

**Participants**

This assessor-blinded, randomized controlled trial was conducted at the Beijing Tsinghua Chang Gung Hospital in China. Inpatients with stroke in the rehabilitation department of the hospital were recruited between March 2019 and August 2019. 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.

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.

**Sample size calculation**
The sample size calculation was conducted using G*Power 3.1.7 (http://www.gpower.hhu.de/). The effect size was estimated using our pilot data regarding decreases in DF stiffness after treatment (study group vs control group: $0.61 \pm 0.21$ vs $0.31\pm0.27$) would be able to reveal a large effect size of Cohen's $d=1.24$, at a power of 0.8 and an $\alpha$ level of 0.05 assuming a non-directional hypothesis. Thus, in the current study, a large effect size $f=0.4$ was assumed in the Mann–Whitney U test model, with an $\alpha$ value of 0.05, power of 0.8, and an attrition rate of 10%, the minimum required sample size was estimated to be 18 participants for this study.

**Experimental design**

A physical therapist who was not involved in this study used a computer to generate a random number table, and designated the random numbers as the study group or the control group according to odd or even numbers. Participants were randomized into the study group and the control group with a 1:1 ratio. The pre-designed random number list was put into the sequentially coded, sealed, and opaque envelope. When a rehabilitation physician not involved in the study was determined that the participants met the conditions, the envelope was opened in order and the participants were enrolled sequentially and assigned to either the study group or the control group. The appointed therapist in charge of the assessment was blinded to the mode of training received by the participants throughout the study period. Participants in the study group had 10 sessions (five times a week over 2 weeks). Each session comprised 20 minutes of 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.

**Experimental Setup**

An ankle rehabilitation robot (Beijing LTK Science and Technology Co., Ltd) was used for intervention and outcome evaluations. While the participant was comfortably seated, the leg of the subject was strapped to a leg support with the knee at 30° flexion and the foot was strapped onto a footplate with ankle dorsiflexion (DF) at 0°. The foot was secured to a footplate at the dorsal side and the heel using adjustable straps. 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). The ankle stretching device was clamped to the chair to avoid movement of the device during stretching [23].

**Stretching Protocol**

The ankle rehabilitation robot was driven by a servomotor controlled by a digital signal processor [16]. Briefly, the stretching velocity was inversely proportional to the joint resistance torque, with the control adjusted at 2000Hz. The maximum stretching velocity was set at 12°/s [24,25]. Typical stretching parameters were 15 to 20 Nm peak resistance torque in dorsiflexion, 5 to 10 Nm peak resistance torque in plantar flexion, and a 5-second holding period at the extreme positions. An experienced physical therapist adjusted the peak resistance torque for each session based on manual stretching and feedback from the
participant during the stretching. There is no break in the process of manual or intelligent stretching training.

**Outcome Measures**

Participants were evaluated before and after the training period by a designated physical therapist blinded to the group assignment. 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 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 $\Delta T$ was the passive torque increment during a certain amount of ankle angular movement ($\Delta \theta$). As $\Delta \theta$ becomes infinitely small, the quasi-static stiffness approaches the slope of a tangential line of the torque-angle curve at a specific ankle position [26,27]. The peak stretching velocity in this study was set at 5°/s to avoid inducing reflex responses [28]. 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 for the PROM of the participants in the two groups all meet this criterion. Three trials were conducted and the averages were taken to be AROM, PROM, muscle strength, and stiffness ($K$).

**Clinical evaluations**

Each subject completed the following functional assessments during clinical evaluation sessions. MAS (0-4 points) was used to measure the calf muscle hypertonia [29]. Fugl-Meyer Motor Assessment of Lower Extremity (FM-LE) (0-34 points) was used to evaluate the sensorimotor function of the lower limbs [30]. The Berg Balance Scale (BBS) (0-56 points) was used to evaluate the balance function. The 6-minute walk test (6MWT) was used to determine walking ability [31]. The Postural Assessment Scale for Stroke Patients (PASS) (0-36 points) was used to evaluate the ability to control posture [32]. The Modified Barthel Index (MBI) (0-100 points) was used to measure the activities of daily living (ADL).

**Pro-Kin balance test**

This study also used the Pro-Kin system 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) [1,33] (Fig. 2). 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 open eyes (OE) and closed eyes (CE). Each test lasted the 30s, with data sampled at
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). Smaller values of the six parameters indicated the participant had a better balance function [34].

**Statistical analysis**

Descriptive data analysis was performed for the collected variables of the participants. Participants’ characteristics measured on a continuous scale were examined using the Shapiro-Wilk test to evaluate normal data distribution. Change with each intervention and during an observation period of two weeks were examined between the groups with a Mann–Whitney U test. The Wilcoxon signed rank test was used to compare pre-and posttreatment measurements in each group. We used Pearson’s coefficient to examine the correlation between stiffness (K) and the Pro-Kin test, and the Kendall rank correlation coefficient ($\tau$) for the correlation between MAS and K. Effects were considered significant if $P < .05$. All statistical analyses were performed with SPSS version 21.0. (IBM Corporation, Armonk, NY, USA).

**Results**

**The flow of the trial and baseline characteristics of participants**

From March 2019 to August 2019, all inpatients in the rehabilitation department were screened. Of these, 43 participants poststroke with ankle spasticity were eligible for evaluation. Among these participants, 20 participants did not meet the inclusion criteria and 3 participants declined to participate in this study (see Fig. 3 for more details). A total of 20 participants were recruited to the study, including 10 participants randomized to the study group, and 10 participants randomized to the control group. All enrolled participants completed the full 2-week treatment, and there were no dropouts or adverse events. There were no significant differences in participants’ characteristics between the two groups (Table 1).

**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 (Wilcoxon signed rank test, $P = .005, .005, .005, and .005$, respectively). The four parameters of biomechanical properties showed similar changes in the control group as in the treatment group (Wilcoxon signed rank test, $P = .017, .005, .005, and .005$, respectively). Besides, significant decreases in DF stiffness and improvements in DF PROM were found for subjects in the study group (Wilcoxon signed rank test, $P = .008, and .041$, respectively) but not in the control group (Wilcoxon signed rank test, $P = .139, and .157$, respectively). No significant differences in biomechanics were found between the two groups after training ($P>0.05$) (Table 2).

**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 (Wilcoxon signed rank test, P = .005, .007, .011, .008, and .041, respectively). We also found significant improvement in FM-LE, BBS, PASS, 6MWT, and MBI in the study group (Wilcoxon signed rank test, P = .007, .012, .026, .008, and .007, respectively). Besides, significant decreases were found in MAS for subjects in the study group (Wilcoxon signed rank test, P = .046) but not in the control group (Wilcoxon signed rank test, P = .317). 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 (Mann–Whitney U test, P = .015) (Table 3).

**Pro-Kin balance test outcomes**

There was no significant difference between the two groups in the 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 (Wilcoxon signed rank test, P = .005, .013, .012, .005, and .041, respectively). The trajectory length and L/M AS with opened eyes decreased significantly after the 2-week training period in the control group (Wilcoxon signed rank test, P = .022, and .042, respectively). No significant difference in the Pro-Kin balance test outcomes was found between the two groups after training (P>0.05) (Table 4).

**Correlations between the stiffness of the ankle and the balance function**

Regarded the two groups as a whole, we further explore the correlations between the stiffness of the ankle and balance before and after treatment. 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 ( =0.352, P=0.026; =0.522, P=0.001; =0.045, P=0.004; =0.433, P=0.005, respectively). The DF stiffness was also significantly correlated with MAS ( =0.265, P=0.041) (Table 5).

**Discussion**

**A. Biomechanical properties of the spastic ankle after stretching**

Several studies have reported the positive effects of stretching subjects with ankle joint spasticity and/or contracture by improving soft-tissue extensibility, and decreasing muscle tone in stroke survivors [11,35,36]. Passive ankle stretching can be applied manually by physical therapists [13,37], external devices [14,38], and robotic systems [39,40]. Manual stretching by moving the spastic ankle through its ROM requires labor-intensive efforts. Furthermore, the outcome of manual stretching exercises is dependent on the experience of the therapist, and several clinical studies have shown insignificant improvements on ankle ROM after manual passive ankle stretching [14,37]. Thus, stretching boards [38] and robotic systems have served as alternative rehabilitation tools for stretching the ankles. Stretching boards have benefits (saving labor cost) and limitations (difficult to adjust the angle dynamically;
inadequate security). The robot-aided rehabilitation of the ankle has been used effectively in treating ankle contracture and/or spasticity with the therapist able to help more patients at less cost and labor [41]. Previous studies indicated that this intervention reduced ankle joint resistance torque and stiffness, increased ROM [16], and improved balance and gait [36] 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 [17]. Waldman [15] investigated the effects of the robotic rehabilitation of the ankle in stroke with ankle impairment, and the results showed patients 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. Forrester [19] conducted similar studies, and the results suggested that robotic rehabilitation of the ankle was effective in improving balance and motor function poststroke.

In this study, to forcefully and safely stretch the ankle of a participant with spasticity to its extreme positions, we used an intelligent stretching device that stretched the joint with real-time feedback control of the resistance torque and stretching velocity. The stretching device was driven by a servomotor controlled by a digital signal processor [42], with the control algorithm described elsewhere [16]. By using this control strategy, the stretching device moved quickly in the middle (non-spastic) ROM and slowed down in the stiffer part of the ROM, while never exceeding preset stretching torques limits. 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 save demanding laborious work and be readily available to participants without the need of a skilled therapist. Furthermore, in this study, a significant correlation ($\tau=0.265$, $P=0.041$) was observed between MAS and DF stiffness, which is consistent with the previous research [43]. This measure of stiffness may be used to obtain a more accurate and quantitative evaluation of biomechanical properties in the future.

B. Balance control

Postural stability, often defined as balance, plays an important role in the recovery of motor function in patients with hemiplegia. Three kinds of strategies are involved in postural control in humans: ankle strategy, hip strategy, and stride strategy [1,44]. 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 [45,46]. The most important roles of the ankle joints are in controlling body sway and forward movements of the lower extremities, and these roles require the sophisticated passive (e.g. bones, ligaments) and active (e.g. muscles) anatomical structures, as well as by the interaction between these structures [47,48]. 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 imbalance.

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, visual feedback training, etc [49-52]. 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, the application of robot-aided rehabilitation of the ankle is aimed at control of the ankle to improve balance function in stroke survivors. 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. The participants 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 simultaneously. This kind of continuous visual feedback combined the correct depiction of proprioceptive and muscular motor sensation, which may ultimately lead to the reestablishment of ankle control. This process may produce various stimuli to the brain, to recover the damaged nervous system and coordination functions.

C. Pro-Kin balance test

Postural stability can be measured by assessing an individual postural sway through changes in the COP. The reliability of COP parameters, such as fluctuation, velocity, and area, to assess the postural control altered by stroke has been investigated [53]. This balance test system only requires participants 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.

In this study, the Pro-Kin was used to quantitatively evaluate the standing static balance of participants 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 [33]. The results showed that, after the intelligent stretching training of the ankle joint, trajectory lengths, elliptical trajectory, L/M SD, F/B AS with closed eyes, and F/B SD with opened eyes decreased significantly, while the control group decreased significantly in trajectory length, and AS M/L with opened eyes, which confirmed that robot-aided rehabilitation of the ankle is of great significance in the implementation of ankle strategy. However, the balance scales failed to reflect the subtle differences in balance function after training between the two groups quantitatively.

Furthermore, we found that there were no significant improvements in trajectory lengths, elliptical trajectory, L/M SD, or L/M AS with opened eyes in the study group after training. As an explanation, we consider the following factors. Control of body balance relies on visual input, proprioception, and input from the vestibular system. The visual information may compensate for the loss of somatosensory function post-stroke and facilitate the human motor program in the brain. A previous study reported that the removal of the visual feedback aggrandized the COP sway [54]. So, stroke patients exhibited decreased postural stability during quiet stance under non-vision conditions, significant differences were easier to find with eyes closed but not open after training [55,56]. Furthermore, the intelligent stretching
positively affected passive ankle stiffness in the sagittal plane (DF-PF), but not in the frontal plane. Previous studies reported that the weaker inter-limb coordination in AP direction after stroke may be on account of impaired balance control, while no significant differences were found in ML-COP fluctuation between two limbs of patients suggested the faint impact of hemiplegia on COP sway in ML direction [57], so there were no significant differences in COP sway in ML direction with opened eyes in the study group after training.

**D. Correlations between DF stiffness and balance**

In a quiet stance, several factors contribute to maintaining an upright position, including postural tone, background muscle tone with neural contributions, and the intrinsic stiffness of the muscle. The stroke survivors must rely on joint and muscle proprioceptors to minimize body movement or loss of balance [58,59]. 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 ( = 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 biomechanical evaluations or Pro-Kin balance test outcomes between the two kinds of interventions were found. This might be because the training frequency, intensity, and total repetitions were not optimal. Third, the long-term effects of intelligent stretching training were unknown for a lack of a follow-up period. Further studies are necessary to address this issue. Our study only investigated the correlations between biomechanical properties and static balance in stroke survivors, the role of ankle function on dynamic balance require further investigation.

**Conclusions**

The robot-aided rehabilitation of the ankles provided well-controlled passive stretching to stroke survivors with ankle impairments, and the benefits included improvements in ankle biomechanical properties, spasticity, balance, motor function, and ADL post-stroke. Findings in this study suggested that robot-
Aided rehabilitation may be a beneficial addition to current rehabilitation programs. As an important part of posture control, ankle function was important in controlling and improving the overall body balance. In particular, ankle dorsiflexion stiffness was correlated with balance performance. As a biomechanical property of the ankle, it may be a sensitive indicator for evaluating the balance performance in 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.

**Declarations**

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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, interpretation of data, and drafting of 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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**Tables**

Due to technical limitations, table 1,2,3,4,5 is only available as a download in the Supplemental Files section.

**Figures**

![Static Balance Assessed by the Pro-Kin System.](image)

**Figure 2**

Static Balance Assessed by the Pro-Kin System.
Supplementary Files

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