ORIGINAL ARTICLE

Effects of Robot-Aided Bilateral Force-Induced Isokinetic Arm Training Combined With Conventional Rehabilitation on Arm Motor Function in Patients With Chronic Stroke

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ABSTRACT. Chang J-J, Tung W-L, Wu W-L, Huang M-H, Su F-C. Effects of robot-aided bilateral force-induced arm training combined with conventional rehabilitation on arm motor function in patients with chronic stroke. Arch Phys Med Rehabil 2007;88: 1332-8.

Objective: To analyze the effects of conventional rehabilitation combined with bilateral force-induced isokinetic arm movement training on paretic upper-limb motor recovery in patients with chronic stroke.

Design: Single-cohort, pre- and postretention design.

Setting: Rehabilitation department at a medical university.

Participants: Twenty subjects who had unilateral strokes at least 6 months before enrolling in the study.

Intervention: A training program (40min/session, 3 sessions/wk for 8wk) consisting of 10 minutes of conventional rehabilitation and 30 minutes of robot-aided, bilateral force-induced, isokinetic arm movement training to improve paretic upper-limb motor function.

Main Outcome Measures: The interval of pretest, post-test, and retention test was set at 8 weeks. Clinical arm motor function (Fugl-Meyer Assessment [FMA], upper-limb motor function, Frenchay Arm Test, Modified Ashworth Scale), paretic upper-limb strength (grip strength, arm push and pull strength), and reaching kinematics analysis (peak velocity, percentage of time to peak velocity, movement time, normalized jerk score) were used as outcome measures.

Results: After comparing the sets of scores, we found that the post-test and retention test in arm motor function significantly improved in terms of grip (P=.009), push (P=.001), and pull (P=.001) strengths, and FMA upper-limb scale (P<.001). Reaching kinematics significantly improved in terms of movement time (P=.015), peak velocity (P=.035), percentage of time to peak velocity (P=.004), and normalized jerk score (P=.008). Improvement in reaching ability was not sustained in the retention test.

Conclusions: Preliminary results showed that conventional rehabilitation combined with robot-aided, bilateral force-induced, isokinetic arm training might enhance the recovery of strength and motor control ability in the paretic upper limb of patients with chronic stroke.

Key Words: Arm; Cerebrovascular accident; Rehabilitation; Robotics.

IT IS ESTIMATED THAT upper-extremity functional recovery is achieved by 79% of acute stroke patients with mild paresis but by only 18% of patients with severe paresis.[1] Traditionally, stroke rehabilitation has been emphasized during the first 3 months after onset, in accordance with the natural history studies of stroke recovery that show a plateau after 3 months.[2,3] Recently, the paradigms for stroke rehabilitation and the period for possible upper-extremity motor recovery has been challenged. Studies in neuroscience have revealed that cortical plasticity is a process that can last for several months. Brain imaging, such as functional magnetic resonance imaging, has shown a cortical reorganization in patients with complete or partial upper-limb recovery.[4-6] These studies show activation not only of the contralateral but also of the ipsilateral sensorimotor cortex and other cortical regions such as the premotor areas, supplementary motor area, and parietal cortex, which suggests the involvement of a widespread network in the recovery of motor function.

A long-term alteration in brain function or cortical reorganization is associated with therapy-induced improvement in the rehabilitation of arm movement after neurologic injury.[7-9] Intervention, which involves massed and sustained practice of functional arm movement, may produce a massive use-dependent cortical reorganization that will provide the basis for a long-term effect of the treatment.[10,11] Results of neuroscience research into brain reorganization and motor recovery may encourage rehabilitation practitioners to develop effective new strategies for the restoration of upper-arm function after stroke or brain lesion.

Traditionally, bilateral movements are encouraged to increase body symmetry and decrease abnormal tone in the early stages of stroke rehabilitation. Recently, several studies[8,12-14] reported that repetitive bilateral arm training is effective in arm and hand motor recovery in stroke patients. It is assumed that bilateral arm training may target facilitation of the affected hemisphere via both indirect and direct corticospinal pathways, and by triggering interhemispheric disinhibition. One study,[15] however, found that short-term bilateral training after unilateral training may have limited effectiveness in enhancing upper-limb motor performance in people with acute and chronic stroke.

In another study[16] of stroke patients, strength was impaired bilaterally but more so on the side contralateral to the brain lesion. Arm weakness in the affected arm of stroke patients is considered a motor control problem involving disorganization of motor output. Research suggests that disorganization factors such as a decrease in the number of motor unit activations, firing rate of motor units, and impairment of motor unit syn-

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chronization, could be eliminated by strength training.[17,18] Thus, strength training is a critical component of any rehabilitation program aimed at regaining upper-limb functional (skillful) movement. Additionally, strength deficits will decrease performance of hand-to-mouth maneuvers, and loss of strength is a more significant contributor to disability in stroke than is loss of dexterity.[19-21] These data attest to weakness (lack of strength) as a factor that should be considered in enhancing the motor performance of patients with stroke.[22] Stein et al[23] reported that robot-aided therapy with active-assisted exercises may be as effective as progressive resistive exercise in increasing force generation in the impaired upper limb after stroke. Bourbonnais et al[24] also showed that force-feedback treatment was not effective in increasing grip strength in patients with chronic stroke. Thus, more studies are needed to identify the most effective training programs for increasing paretic arm strength in stroke patients.

Robot-assisted motor rehabilitation has rapidly developed since the 1990s.[25,26] MIT-Manus and the mirror-image motion enabler are sophisticated robot devices for training of arm recovery in stroke rehabilitation. Results from clinical trials of robot-aided therapy show that proximal arm strength and motor function improved after robot-aided training.[26-29] It is believed that robot-aided therapy and the bilateral approach to arm rehabilitation may offer a patient more intensive practice opportunities without increasing the time the treating therapist spends in supervision. For example, Hesse et al[30] reported severely affected stroke patients (in the subacute stage) regained upper-limb motor control and power after training with a computerized arm trainer.

Bilateral symmetric push and pull movements with resistance can be used to simulate sanding activity, which is among the popular therapeutic activities in early rehabilitation. Apart from this, resistance movements performed with a slow and constant velocity may not provoke the stretch reflex during exercise. Studies[31,32] have shown isokinetic strength training may improve paretic lower-limb function in stroke patients. Few studies, however, have evaluated the effect of isokinetic strength training on paretic upper-limb recovery. For this study, we hypothesized that chronic stroke patients would benefit from affected upper-limb motor training if we included in the conventional rehabilitation program a robot-aided device to provide bilateral symmetric upper-limb movement and isokinetic strengthening.

METHODS

Participants

We recruited 20 subjects (12 men, 8 women) from the outpatient rehabilitation service to participate in this study. Eighteen subjects were right-handed. The patients were between ages 36 to 80 years (mean $\pm$ standard deviation [SD], 57.1 ± 14.0y) and had unilateral lesions (cortical, $n=14$; subcortical, $n=6$; left hemisphere, $n=9$; right hemisphere, $n=11$) identified by neuroimaging done at least 6 months before the pretest (mean, 35.4 ± 36.6mo). The subjects' Fugl-Meyer Assessment (FMA) scores for upper-limb motor function[33] ranged from 6 to 55. Criteria for inclusion included: (1) no specific perceptual-cognitive dysfunction that could limit comprehension of the experimental task; (2) no severe concurrent medical problems such as shoulder pain and orthopedic conditions affecting arm movements; (3) able to exert push and pull forces greater than .98N with the paretic upper limb; and (4) no uncontrolled cardiopulmonary diseases. All subjects gave their informed consent and our institutional review board approved all study procedures.

Instrument and Intervention

We used a simple robot-aided device called the bilateral force-induced isokinetic arm movement trainer (BFIAMT) in the study. The device provides 4 different treatment modes: bilateral passive, bilateral active-passive, bilateral reciprocal, and bilateral symmetric arm movement. The BFIAMT has the following components: 1 control panel system, 2 load cells, 2 servomotors, 2 roller guides, 2 cone-shaped handles, and 2 forearm troughs (fig 1).

Following Mudie and Matyas's suggestion for arm movement training,[12] we used the bilateral symmetric arm movement treatment mode to train the affected and unaffected upper

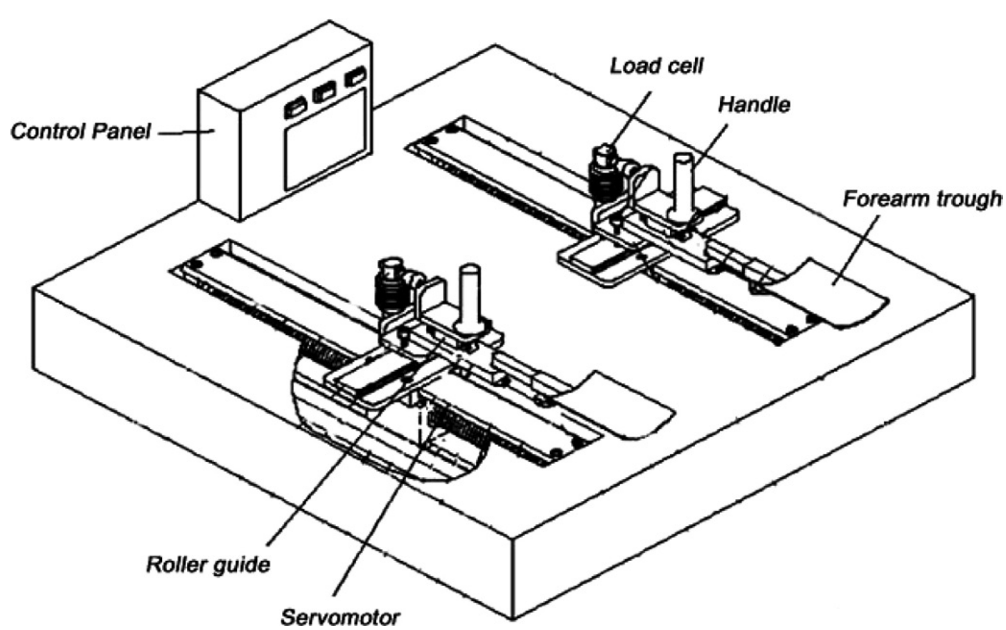

Fig 1. The BFIAMT and its component parts.

limbs in this study. This mode can simulate symmetric bilateral sanding activity and allows the subject to practice a bilateral symmetric push (shoulder flexion and elbow extension) and pull (shoulder extension and elbow flexion) movement at a preset constant velocity. When the bilaterally exerted push and pull forces (detected by 2 load cells in the device) are concurrently greater than the preset demanded forces for the affected and unaffected upper limbs, the control system drives the servomotor and lets the 2 cone-shaped handles move in a symmetrical and smooth manner. Accordingly, the resistances of both upper limbs would be equal to the forces exerted by both of the subject's limbs. If any forces exerted by the upper limb cannot reach the preset demanded force criterion, the servomotor stops and no movement occurs. The moving speed of the cone-shaped handles can be set beforehand to a subject's preferred pace. This mechanism allows a subject with moderate to mild upper-limb impairment to perform symmetric resistive isokinetic push and pull movements bilaterally. In addition, the mechanism can help a subject with severe upper-limb impairment perform smooth isokinetic push and pull movements bilaterally. The device can also be used to assess unilateral or bilateral isometric upper-limb pull-push forces by setting the movement velocity to zero.

Subjects participated in 24, forty-minute treatment sessions over an 8-week period. A treatment session was in 2 parts. In part 1 (30min) subjects completed 3 consecutive sets of 20 repetitions of bilateral symmetric arm push and pull movements with the BFIAMT. A subject's isometric maximal arm push and pull strength in both the affected and unaffected upper limbs were identified before treatment. The preset demanded forces for the 3 sets were 10%, 20%, and 10% of maximal push and pull forces of the affected and unaffected arms. Additionally, subjects were instructed to perform bilateral symmetric push and pull movements at a comfortable cycling pace; the most preferred cycling frequency was 0.1Hz. During treatment, subjects were seated and encouraged to push and then pull (1 repetition) the 2 cone-shaped handles to generate smooth, bilateral symmetric movements with exerting forces greater than the preset demanded forces. The length of a subject's upper limb determined the push-pull movement distance, which ranged from 35 to 45cm. The force demanded of the affected arm of subjects with severe upper-limb impairment could be set at zero.

The affected forearm was supported with a forearm trough and the affected hand was strapped to the cone-shaped handle to ensure that a subject pushed and pulled the handles bilaterally (fig 2). Such adaptations helped severely impaired subjects perform bilateral active-assistive arm movement practices. During training, the subject's bilateral push and pull forces (exerted on the handles that were connected to the load cells) could be detected and displayed in the control panel. These force data were shown in real time to the subject for visual feedback so as to keep his/her attention focused on the treatment. Generally, the subjects had to keep exerting the demanded forces bilaterally for 10 seconds to complete a smooth push and pull movement. A belt that was fixed to the back of the chair restricted trunk compensatory movement across the lower thorax. A 5-minute rest was allowed between sets to prevent fatigue.

In part 2 of the treatment (10min), subjects received a specific conventional rehabilitation program focused on treatment that did not provide symmetric bilateral movement and resistance trainings to the upper limbs. This program included range of motion exercise, affected arm muscle tone normalization, compensatory activity of daily living training, postural control training, and gait correction. The program was provided

Fig 2. A subject with severe arm motor impairment practices with the robot-aided BFIAMT. The affected hand is fastened to the handle with a bandage. The control panel shows the subject the maximal force exerted during each push and pull movement.

to ensure that all rehabilitation needs of each subject were met during the study.

In the follow-up stage, all subjects participated in 24, forty-minute sessions of regular occupational therapy (20min/session) and physical therapy (20min/session), based on the neurodevelopment therapy, over an 8-week period.

Outcome Measures

The measuring therapist and treating therapist were different medical personnel. Motor functions of the affected arm were evaluated with arm motor tests and kinematic analysis of reaching with the affected arm. Motor function tests of the affected arm included isometric grip strength, push strength, pull strength, FMA, Frenchay Arm Test (FAT),[34] and the Modified Ashworth Scale (MAS).[35] We assessed the arm reaching function of subjects who showed reaching ability with the affected arm in a pretest (n=15). The following kinematic dependent variables were derived from the marker position to examine and quantify the affected arm reaching movement: peak velocity (in cm/s), percentage of time to peak velocity (PTPV), movement time (in seconds), and normalized jerk score (NJS).

We tested grip strength of the affected upper limb with the Jamar dynamometer.[a] Measurements of the limb's push-pull strength were obtained from the BFIAMT. The testing position for the maximal isometric push-pull strength test was as follows: subjects were seated in an upright position with both arms and shoulders adducted, elbows flexed at 90°, and forearms in the neutral position. To prevent compensatory trunk movement during the testing, they were restrained to the chair back with a strap positioned at the lower thorax. An increase of 25% in push or pull strength across the 3 trials was considered to be inappropriate involvement of trunk compensation. Subsequently, additional trials were conducted. Subjects rested for 5 minutes between tests. Three successful trials of maximal grip, push, and pull strengths were obtained for each subject.

We used a 3-dimensional optical motion capture system[b] to collect the movement trajectories of the affected arm. An infrared light-emitting diode was positioned on the ulnar styloid process. During testing, subjects were seated in an upright position with the trunk restrained to the chair back and the wrist of the affected arm resting on the desk border. The elbow was flexed at an angle of 90° and the shoulder adducted to the trunk. Subjects were requested to reach and touch a cup, without picking it up, as rapidly as possible. The cup was

Table 1: Arm Motor Function Scores (Pretest, Post-Test, and Retention Tests) of the 20 Subjects

Motor Function	Pretest	Post-Test	Retention Test	F	*P*
FMA	32.70±15.26	35.55±14.50	35.35±14.63	15.09	.001
FAT	1.75±2.24	1.80±2.23	1.80±2.23	1.00	.33
MAS	0.95±0.74	0.77±0.63	1.00±0.70	1.18	.31

NOTE. Values are mean ± SD.

placed on the table at a distance the length of the subject's upper limb. Each subject completed 5 reaching trials.

The position of the marker on the wrist was recorded at a sampling rate of 70Hz and digitally filtered with a low-pass second-order forward and backward Butterworth filter with a cutoff frequency set at 5Hz.

Data Reduction and Analysis

We analyzed the kinematic data of the arm reaching trajectories with the VZAnalyzer software, version 3.0.[b] The software gave a 3-dimensional reconstruction of the marker positions. A relative velocity above or below 10% of the maximum movement velocity on the sagittal plane (*z* axis), which was parallel to the reach movement direction, was used to detect the start and end of each reaching movement.[36] Peak velocity (the highest instantaneous velocity during the reaching movement) was regarded as being correlated with the force generation of a movement.[37-39] Movement strategy measure was analyzed from peak velocity relative to movement time. A left shift of the peak in the velocity profile (decreased PTPV) indicates more time spent in deceleration, or a guided movement strategy is used.[40,41] Movement time (the duration of execution of a movement) reflects the overall speed of a movement, as a faster movement would result in a shorter movement time. We used a NJS to quantify the movement smoothness. It provides information about the smoothness and efficiency of a movement; a lower NJS indicates a smoother and more efficient reaching movement.[42,43] Because jerk increases dramatically with movement duration and the distance traveled during the movement, it was useful to normalize this quantity in time and distance. To obtain the NJS, we used a mathematical formula to compute the jerk. This was done by introducing the term t^5/s^2 into the formula for the NJS.[44,45] The formula was taken as:

$$\mathrm{NJS} = \sqrt{\frac{1}{2}\int\left(\left(\frac{d^3x}{dt^3}\right)^2+\left(\frac{d^3y}{dt^3}\right)^2+\left(\frac{d^3z}{dt^3}\right)^2\right)dt\left(\frac{t^5}{s^2}\right)}$$

where *x* is the position of the hand on the *x* axis, *y* is the position of the hand on the *y* axis, *z* is the position of the hand on the *z* axis, *t* is movement time, and *s* is movement distance of the hand.

The outcome measures, including upper-limb motor function and reaching kinematics, were conducted at pretest, post-test, and retention test. We used repeated-measure analysis of variance to test the effects for significant motor and kinematics outcome changes. All statistical tests were conducted with the α level set at .05. When significant within-subject effect was found, we used the Bonferroni adjustment in the multiple comparison tests.

RESULTS

Table 1 shows the affected arm motor scores at pretest, post-test, and retention test measures. There was significant within-subject effect in FMA (F=15.09, $P<.001$). Multiple comparison tests revealed that both the post-test and retention test scores were higher than the pretest scores (reflecting about a 3-point increase) and there was no significant difference between post-test and retention test scores. The FAT and MAS scores did not show significant differences across the pretest, post-test, and retention test scores.

There was significant within-subject effect in push strength (F=8.98, $P<.001$), pull strength (F=9.34, $P<.001$), and grip strength (F=5.65, $P<.01$). Multiple comparison tests showed that the push, pull, and grip strengths in both post-test and retention test scores were all higher than in the pretests (reflecting 44.39, 33.81, and 21.65N increases, respectively). The push, pull, and grip strengths did not reveal significant differences between the post-tests and retention tests (table 2).

The affected arm-reaching ability of 15 subjects was further analyzed with kinematic measurements. Table 3 shows the reaching kinematic scores of the pre-, post-, and retention tests. There was significant within-subject effect in movement time (F=4.91, $P<.05$), peak velocity (F=4.39, $P<.05$), PTPV (F=6.70, $P<.01$), and NJS (F=5.68, $P<.01$). Multiple comparison tests showed all kinematic variables had significant differences between pretest and post-test scores, but not between post-test and retention test scores, or between pretest and retention test scores.

DISCUSSION

Our findings demonstrate that motor recovery in a paretic upper limb might be enhanced with an 8-week, robot-aided training program using the BFIAMT. These major recovery components comprised increasing paretic upper-limb grip strength, push and pull strengths, motor function, and reaching control. Muscle tone and FAT scores did not show significant changes across the pre-test, post-test, and retention test scores.

Bilateral arm movement would enhance interhemispheric motor cortex disinhibition that is likely to facilitate reorganization by sharing normal movement commands from the undamaged hemisphere[46] and permitting overflow.[14] We hypothesized that by practicing with the BFIAMT, the number of

Table 2: Grip and Push and Pull Strengths of 20 Subjects for the Pretest, Post-Test, and Retention Test

Strength	Pretest	Post-Test	Retention Test	F	*P*
Push strength (N)	83.30±85.16	127.69±107.50	135.53±109.46	8.98	.001
Pull strength (N)	91.23±58.99	125.04±71.44	131.51±72.32	9.34	.001
Grip strength (N)	73.90±64.68	95.55±71.73	90.84±70.76	5.65	.009

NOTE. Values are mean ± SD.

Table 3: Scores of 15 Subjects for the Reaching Kinematics Pretests, Post-Tests, and Retention Tests

Kinematics	Pretest	Post-Test	Retention Test	F	*P*
Movement time (s)	1.24±0.45	0.80±0.29	1.02±0.58	4.91	.015
Peak velocity (cm/s)	81.14±34.71	100.40±38.33	82.48±36.46	4.39	.035
PTPV (%)	31.10±9.45	40.80±12.42	35.30±10.67	6.70	.004
NJS	173.35±114.10	76.15±69.44	136.94±93.95	5.68	.008

NOTE. Values are mean ± SD.

motor unit activations, increases in neural drive, and "overflow" effects might be more marked. Another possible contributive factor is that the BFIAMT might have enhanced a balancing effect on the between-hemisphere cortical motor excitability[46-48] that is associated with brain reorganization,[8] and thus contributed to motor recovery. Brain reorganization studies with functional magnetic resonance imaging and electromyography are needed to confirm these assumptions.

The BFIAMT is designed to permit subjects to practice bilateral arm movement exercises with relatively slow and constant velocity to prevent provoking a stretch reflex. The device can induce subjects with severe levels of arm impairment to practice a full range of smooth, repetitive bilateral push and pull movements by detecting whether the strength being exerted is greater than the preset value. Such a mechanism will be beneficial to the subject in experiencing normal proprioceptive feedback while controlling bilateral multijoint arm movement.[49,50] For subjects with moderate to mild arm impairments, the BFIAMT will provide isokinetic bilateral arm resistive push and pull movement practice; this may enhance the recovery of arm function for less impaired subjects.[51] In this study, each subject needed to perform a total of 1440 repetitions of a bilateral shoulder-elbow coordinated movement while exerting submaximal push and pull strength. At the same time, subjects with active grasp ability needed to firmly hold the cone handles with both hands during the push and pull movement. Isometric grip strengths of both hands were also trained during the exercise. Thus, training with the BFIAMT demands that the patients learn control of bilateral activation with symmetric loading and upper-limb multijoint coordinative movement.[52] The loading demand was greater than movement repetition in BFIAMT training. Additionally, a meta-analysis[53] of studies of unilateral strength training showed that an average of 7% of initial strength, or about one quarter of the increase in strength on the trained limb, will transfer to the untrained limb after unilateral training. Because of the neural adaptations to resistive exercise, the training effects in the unaffected upper limb might lead to training effects in the affected upper limb after BFIAMT training.[54,55] Therefore, the gains (as a percentage of the variable) in strength (grip, push, and pull) from BFIAMT training were at least 3 times greater than the gains in motor function, as assessed with the FMA. Such findings could both support our hypothesis and imply that the BFIAMT might be an appropriate therapeutic modality for strengthening the paretic upper limb in chronic stroke patients.

Kinematic analysis of arm reaching is considered a sensitive and objective method for analyzing upper-limb interjoint coordination and control strategy.[56] Studies of recovery from neural injury suggest that movement smoothness is a result of learned interjoint coordination and it will increase with motor recovery in subjects with movement disorders.[42,57] Peak velocity is considered to be linearly related to the force that is generated during movement process,[58] and the location of peak velocity in the velocity profile is one indication of the control strategy used. For a normal preplanned movement, peak is located at 33% to 50% of the velocity profile, and the left shift of the peak in the velocity profile indicates increasing dependence on a visually guided strategy[40,59] during reaching. Although there were improvements in reaching ability in the affected upper limb after BFIAMT training, retention test scores revealed that training gains in reaching control had significantly declined after 8 weeks. On the other hand, retention test scores of the paretic upper-limb motor function tests did not show a significant decrease. Such results reflect the idea that intensive bilateral activation with loading control training might enhance the maintenance or improvement of the control strategy and interjoint coordination of the paretic upper limb. Incidentally, our result shows that kinematic analysis may provide a sensitive way to monitor the early changes of treatment effects on upper-limb interjoint coordination and motor function.

Previous studies, designed to investigate the effects of 6 to 8 weeks of specific therapy on paretic upper limb in patients with chronic stroke (at least 6mo since onset), showed significant gains in FMA scores, ranging from 2.8 to 3.5.[13,23,26,27] The significant gain in FMA scores (2.9) in our study was within the gain range of previous studies. We did not, however, find a significant improvement in FAT scores after BFIAMT training. We inferred that the gain in FMA scores might not reach a level significant enough to improve paretic upper-limb performance and to reflect such ability in FAT tasks. Finger coordination abilities when manipulating small objects also play an important role in hand function performance. Training with the BFIAMT, however, is not supposed to yield enhanced antigravity arm strength and finger dexterity control. Thus, using the BFIAMT with the robot-aided device set on an inclined plane, combined with distal motor and fingers dexterity control training, may improve paretic upper-limb performance in activities of daily living.

Study Limitations

We used a single-cohort design with no control group and concurrent physical and occupational therapies during the treatment stage and the retention stage. The incorporation of occupational and physical therapies into the treatment stage might limit the validity of BFIAMT training effects. We did not use electromyography to monitor the trunk muscle activities and we did not perform standardized measurements of arm push and pull tests in the study, thus the possible compensation of trunk movement during maximal isometric push and pull tests cannot be excluded. These confounding factors may have a bearing on our findings and precautions are needed in the application of our results. We did not assess the effects of conventional rehabilitation combined with BFIAMT training on bilateral arm reaching ability and bimanual arm ability. Accordingly, we recommend that the contribution of BFIAMT training to bimanual arm function be studied further. In the future, a group comparison with random assignment design and recruiting samples with subacute or chronic subjects could be made to analyze the effect of BFIAMT training on the paretic upper limb. Finally, further investigations are needed to test whether bilateral training is superior to unilateral training in the recovery of paretic upper-limb motor function following stroke.

CONCLUSIONS

This study suggests that conventional rehabilitation, combined with 24 sessions of robot-aided therapy in the form of BFIAMT training over an 8-week period, may be beneficial for chronic stroke patients in recovering paretic upper-limb strength and motor control ability. It may provide an alternative therapy for the upper-limb rehabilitation of the stroke population in both clinical and community situations. Future study with randomized controlled trials is required to assess its effectiveness.

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