Effect of Therapist-Based Versus Robot-Assisted Bilateral Arm Training on Motor Control, Functional Performance, and Quality of Life After Chronic Stroke: A Clinical Trial

Ching-yi Wu, Chieh-ling Yang, Li-ling Chuang, Keh-chung Lin, Hsieh-ching Chen, Ming-de Chen, Wan-chien Huang

Background. Although bilateral arm training (BAT) has been widely studied, the comparative effects of therapist-based BAT (TBAT) versus robot-assisted BAT (RBAT) remains unknown.

Objective. This study compared the efficacy of TBAT, RBAT, and a control treatment (CT) on motor control, functional performance, and quality of life after chronic stroke.

Design. A randomized, pretest-posttest, control group design was used.

Methods. Forty-two patients (mean age=54.49 years, SD=9.69; mean length of time since stroke onset=17.62 months, SD=10.50) were randomly assigned to TBAT, RBAT, and CT groups. Each group received treatment for 90 to 105 minutes per session, 5 sessions on weekdays, for 4 weeks. Outcome measures included kinematic analyses, the Fugl-Meyer Assessment (FMA), the Motor Activity Log, and the Stroke Impact Scale (SIS).

Results. Large and significant effects were found in the kinematic variables, distal part of upper-limb motor impairment, and certain aspects of quality of life in favor of TBAT or RBAT. Specifically, the TBAT group demonstrated significantly better temporal efficiency and smoothness, straighter trunk motion, and less trunk compensation compared with the CT and RBAT groups. The RBAT group had increased shoulder flexion compared with the CT and TBAT groups. On the FMA, the TBAT group showed higher distal part scores than the CT group. On the SIS, the RBAT group had better strength subscale, physical function domain, and total scores than the CT group.

Limitations. This study recruited patients with mild spasticity and without cognitive impairment.

Conclusions. Compared with CT, TBAT and RBAT exhibited differential effects on outcome measures. Therapist-based BAT may improve temporal efficiency, smoothness, trunk control, and motor impairment of the distal upper limb. Robot-assisted BAT may improve shoulder flexion and quality of life.

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Patients with stroke often have adaptive compensation by using alternative movement patterns during task accomplishment,[1] such as forward trunk inclination for reaching when elbow extension or shoulder flexion is limited.[2] Trunk compensation for motor impairment engenders a pattern of disuse that might restrict motor improvement of the upper limb (UL).[1,3]

Bilateral arm training (BAT) is a promising treatment approach that improves UL function after stroke.[4,5] This treatment approach usually involves the repetitive practice of bilateral, symmetrical movement of whole-arm functional training, which usually is supervised and mediated by a therapist (TBAT)[4] or a robot (RBAT).[6] Previous TBAT studies showed positive outcomes for reducing UL impairment,[7,8] enhancing motor function,[8] and increasing movement smoothness and force generation during reaching.[8,9] However, TBAT requires extensive therapist guidance for treatment delivery; RBAT has emerged as an alternative approach to save manpower and costs by decreasing the time demands on the therapist.

Robot-assisted BAT involves simultaneous, active movements of both limbs with a robot providing assistance or resistance.[6] This treatment approach has demonstrated beneficial effects on motor impairment[6,10,11] and muscle strength,[6,10,11] but not on functional independence or on capacities for basic daily activities.[10–12] Proper wrist and hand use is particularly relevant for functional use of the paretic arm in daily life,[13] and functional gains depend more on wrist and hand movement.[14] Training of the distal UL leads to twice as much carryover effect to the proximal segments than in the reverse order of training.[15] Therefore, training of bilateral forearms and wrists was adopted in this study for RBAT.

Taken together, BAT mediated by therapists or by robots has demonstrated benefits for motor or functional improvement. Therapist-based BAT involves multijoint, against-gravity, and function-oriented tasks, whereas RBAT involves single-joint, gravity-eliminated, and motor skill–oriented tasks. The different nature of training content in the 2 approaches may result in differential effects. The purpose of this study was to compare the efficacy of TBAT, RBAT, and a control treatment (CT) on kinematic analysis, functional outcome, and quality of life. Kinematic analysis provides information not only on movement quality of the UL (eg, movement directedness, smoothness, efficiency) but also on the extent of trunk compensation to reaching tasks.[15]

Method

Participants

We recruited 42 participants who met the following inclusion criteria: (1) onset of a unilateral stroke at least 6 months previously; (2) mild-to-moderate motor impairment (total score of 26–66 on the Fugl-Meyer Assessment [FMA] for the UL)[11,16]; (3) no severe spasticity in the paretic arm (Modified Ashworth Scale score of ≤ 2 in any joint)[17]; (4) no serious cognitive deficits (Mini-Mental State Examination score of ≥ 22)[18]; (5) no other neurologic, neuromuscular, or orthopedic disease; and (6) no participation within the previous 3 months in any experimental rehabilitation or drug studies. All participants provided informed consent before data collection.

Design

A randomized, pretest-posttest, control group design was used in this study. Eligible participants were individually randomized to TBAT, RBAT, and CT groups (Fig. 1). A prestratification strategy was applied according to side of the lesion and severity of the motor impairment (total score on the FMA for UL: 26–40 versus 40–66)[11] to ensure an equal distribution of the participants in each group. The allocation to group was concealed from the investigators, and the participants were blinded to the study hypotheses.

Training was administered during outpatient occupational therapy sessions, in which each participant received TBAT or RBAT, depending on group allocation, along with 15 to 20 minutes of UL functional training to achieve individual treatment goals. All other routine interdisciplinary stroke rehabilitation that did not focus on UL training was continued as usual. Clinical outcome measures were administered at baseline and immediately after a 4-week intervention by certified, trained occupational therapists blinded to the participant group.

Interventions

All participants received a 90- to 105-minute therapy session, 5 times per week, for 4 weeks. The intervention was provided at the participating hospitals under the supervision of certified occupational therapists trained to deliver standardized treatment and monitor the safety of patients undergoing the intervention.

TBAT group. The TBAT group was asked to practice identical tasks with each arm simultaneously. Participants moved the unaffected arm voluntarily while also attempting to move the affected arm voluntarily. For those who had difficulty moving the affected arm simultaneously with the unaffected arm, therapists provided physical assistance to the affected arm. Participants practiced a variety of bilateral functional tasks under one-on-one supervision of the therapists. Among the tasks were lift 2 cups, stack 2 checkers, reach forward or upward to move blocks, grasp and release 2 towels, and manipulate 2 coins simultaneously by each hand. The TBAT group also practiced 15 to 20 minutes of functional training and 5 minutes of tone normalization at the end of therapy, if necessary. Participants received verbal feedback, including knowledge of results (KR), referring to task success of failure, and knowledge of performance (KP), referring to the nature of movement pattern.[19] Examples of KR include “the movement was correct” and “you missed your target,” and examples of KP include “move your trunk less” and “pick up the block faster.”

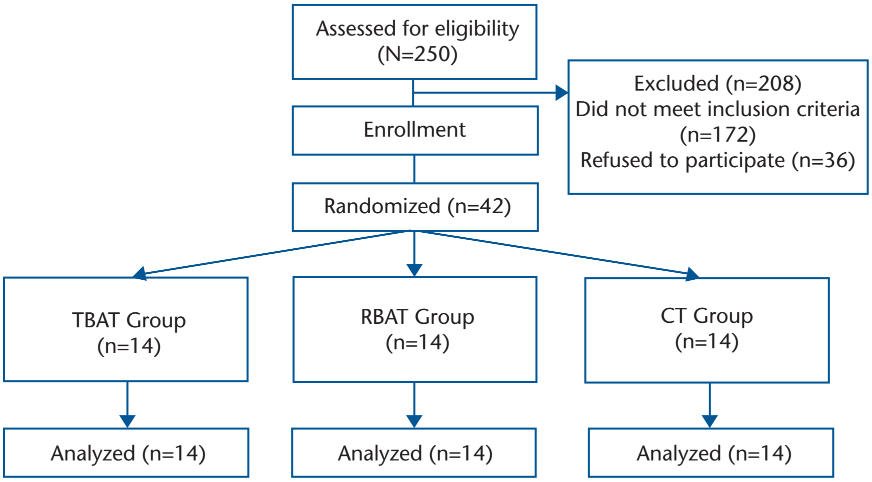

Figure 1.
Flow diagram showing the randomization procedure. RBAT=robot-assisted bilateral arm training, TBAT=therapist-based bilateral arm training, CT=control treatment.

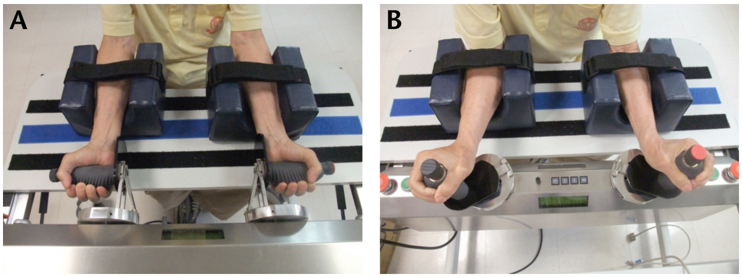

Figure 2.
The Bi-Manu-Track. (A) Pronation and supination movement of the forearm. (B) Flexion and extension movement of the wrist.

RBAT group. The Bi-Manu-Track (Reha-Stim Co, Berlin, Germany; Fig. 2) robot-assisted arm trainer was used.[6,20] Participants sat at a height-adjustable table with elbows at 90 degrees. They grasped the 3-cm-diameter handles with each hand or both hands, and their forearms were placed in the midposition into the arm troughs. A computer game (eg, picking up and placing apples) that tracked participants’ movements facilitated participation.

The Bi-Manu-Track offers 2 movement patterns: forearm pronation-supination and wrist flexion-extension. There are 3 operational modes: passive-passive mode (mode 1), with both arms being passively moved by the machine; active-passive mode (mode 2), with the nonparetic arm driving the paretic arm to move symmetrically; and active-active mode (mode 3), with both arms performing actively by overcoming resistance. Participants spent about 30 minutes in modes 1 and 2 and about 10 minutes in mode 3 for each type of movement. They received 75 to 80 minutes of RBAT, followed by 15 to 20 minutes of unilateral and bilateral functional training and 5 minutes of tone normalization at the end of therapy, if necessary. The safety features of Bi-Manu-Track include mechanical braking of the movement when the torque exceeds 4 N·m, preventing injuries caused by excessive passive movement on the affected arm, and an emergency brake within reach of the user that enables the user to stop the arm trainer whenever he or she feels uncomfortable.[21]

CT group. The therapeutic activities in the CT group involved weight bearing, stretching, strengthening of the paretic arms, coordination, unilateral and bilateral fine motor tasks, balance, and compensatory practice on functional tasks.

Outcome Measures

Kinematic analysis. Experimental tasks included 1 unilateral task of pressing a desk bell and 1 bimanual task of pulling open a drawer to retrieve an eyeglass case. Participants sat on a height-adjustable, straight-back chair with the seat height set to 100% of the lower leg length. In the initial position, the tested arm was pronated and the hand rested on the edge of the table in a neutral position with 90 degrees of flexion at the elbow joint. The target object (desk bell or drawer) was placed in the midline of the body. The reaching distance was standardized to the participant’s *functional arm length*, defined as the distance from the medial border of the axilla to the distal wrist crease.[22] If the maximum distance the participant could reach was less than the functional arm length, the reaching distance to the target was adjusted to the maximum reachable distance. No or minimal trunk movement occurs when an individual who is healthy reaches for a target within arm's length.[2] For the unilateral task, the tester's instruction to the participants was: "When I say 'go,' please use the index finger of the affected hand to reach and press the task bell as fast as possible." For the bimanual task, the instruction given to participants was: "When I say 'go,' please pull a drawer with the affected hand and retrieve an eyeglass case inside the drawer with the unaffected hand at a comfortable self-speed." Only the pulling phase was analyzed. After a practice trial, 3 data-producing trials were performed.

A 7-camera motion analysis system (VICON MX, Oxford Metrics Inc, Oxford, United Kingdom), recording at 120 Hz, was used with a personal computer to capture the movement of 17 markers that were placed on the participants' sternum, spinal process (C7 and T4), bilateral thumbnails, index fingernails, ulnar styloid processes, radial styloid processes, lateral epicondyles, middle part of the humeri, acromial processes, and clavicular heads. The system was calibrated to have averaged residual errors not exceeding 0.5 mm for each camera before data acquisition. For the unilateral task, 1 channel of analog signals was collected to signal the end of the movement when the bell was pressed. *Movement onset* was defined as a rise of tangential wrist velocity above 5% of its peak value for both testing tasks. *Movement offset* for the unilateral task was defined as the time when the participant pressed the bell. During the bimanual task, *end of movement* was defined as a fall of tangential wrist velocity below 5% of its peak value. Movements were digitally low-pass filtered at 5 Hz using a second-order Butterworth filter with forward and backward pass.

Data reduction for kinematic variables. An analysis program coded by LabVIEW (National Instruments Inc, Austin, Texas) language was used to process the kinematic data. Kinematic variables were chosen to describe the arm-trunk movement quality and trunk compensation. Movement quality involved reaching performance characterized by normalized movement time (NMT) and normalized movement units (NMUs), and trunk movement was characterized by normalized trunk displacement (NTD). Movement time (MT) is the interval between movement onset and offset, which refers to the time for execution of the reaching movement and represents temporal efficiency.[22,23] One movement unit (MU) consists of 1 acceleration phase and 1 deceleration phase, which characterizes movement smoothness. Fewer MUs indicate smoother movement.[23] The MT and MU were divided by the reaching distance to normalize for variations in reaching distance across participants and denoted as NMT and NMU, respectively. Furthermore, NTD was expressed as trunk total displacement of the sternum marker divided by trunk distance,[24,25] which is illustrated in Figure 3.

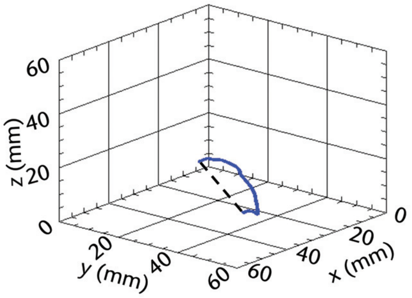

Figure 3.
Normalized trunk displacement denoted by trunk total displacement/trunk distance is illustrated: the solid line means trunk total displacement; the dashed line means trunk-moving distance.

Trunk compensation changes were denoted by the *trunk contribution slope*, which is defined as the ratio of the sagittal translation of the index minus that of the sternum marker to the sagittal translation of the sternum marker, indicating the amount of trunk displacement on reaching. The lower the slope value, the more compensation (or displacement) the trunk exerted.[2] Trunk movement in adults who are healthy usually occurs at earlier phases of reaching. Accordingly, we divided the reaching movement equally into 3 phases, calculated the slope separately for each phase, and used the slope values at the start and middle phases as the dependent variables.[2] The angular changes of the shoulder and elbow joint refer to the differences in shoulder and elbow angle from movement onset and movement offset and were divided by the reaching distance to normalize for variations in reaching distance across participants.[24,26]

Clinical assessment. The UL subscale of the FMA, which assesses motor impairment, consists of 33 items measuring the movement and reflexes of the shoulder/elbow/forearm, wrist, and hand and coordination/speed on a 3-point ordinal scale (0=cannot perform, 1=can perform partially, 2=can perform fully).[27] The proximal and distal scores of the FMA were calculated to examine the treatment effects on separate UL elements of movement. A higher FMA score indicates less motor impairment.

The Motor Activity Log (MAL) evaluates daily functions by using a semi-structured patient interview that assesses the amount of use (AOU) and quality of movement (QOM) of

Table 1.
Characteristics of Study Participants (n=42)[a]

Variable	RBAT Group (n=14)	TBAT Group (n=14)	CT Group (n=14)	Statistic[b]	*P*
Sex, n				1.05	.59
Male	10	12	10		
Female	4	2	4		
Age, y, $\bar{X}$ (SD)	55.13 (12.72)	57.04 (8.78)	51.30 (6.23)	1.29	.29
Side of brain lesion, n				1.41	.49
Right	7	5	4		
Left	7	9	10		
Months after stroke onset, $\bar{X}$ (SD)	18.00 (8.65)	17.29 (13.29)	17.57 (9.80)	0.02	.99
MMSE score, $\bar{X}$ (SD)	27.71 (2.33)	28.57 (1.70)	28.08 (1.50)	0.73	.49

[a] RBAT=robot-assisted bilateral arm training, TBAT=therapist-based bilateral arm training, CT=control treatment, MMSE=Mini-Mental State Examination.
[b] Statistic associated with the chi-square test or the Fisher exact test for categoric variables and with the analysis of variance for continuous variables.

the affected UL in 30 daily activities.[28] The MAL uses a 6-point ordinal scale, with higher scores indicating better performance.

The Stroke Impact Scale (SIS), version 3, is a 59-item self-report scale designed to assess quality of life. It is grouped into 8 functional subscales: strength, memory, emotion, communication, activities of daily living (ADLs)/instrumental ADLs (IADLs), mobility, hand function, and participation. The strength, hand function, ADLs/IADLs, and mobility subscales can be combined into a composite physical function domain.[29] Items are rated on a 5-point Likert scale, with lower scores indicating greater difficulty in task completion during the previous week. Aggregate scores, ranging from 0 to 100, are generated for each subscale.

Data Analysis

Baseline differences between groups were evaluated with the chi-square test or the Fisher exact test for categoric data and analysis of variance (ANOVA) for continuous data. Given that our research aimed to compare whether the posttest results were different among the 3 groups, analysis of covariance (ANCOVA) is a more suitable statistical method than repeated-measures ANOVA to compare the intervention main effect (ie, posttest score) by holding the pretest score constant in the former method.[30] For the ANCOVA, pretest performance was the covariate, group was the independent variable, and posttest performance was the dependent variable. To index the magnitude of group differences in performance, $\eta^2=SS_b/SS_{total}$ was calculated for each outcome variable, where SS is the sum of squares and b represents between-groups. The value of η^2 is independent of sample size and represents the variability in the dependent variable (posttest performance) that can be explained by group.[31] A large effect is represented by an η^2 of at least .14, a moderate effect by an η^2 of .06, and a small effect by an η^2 of .01.[32] Least significant difference was used to determine the *post hoc* significance of pair-wise comparisons of adjusted group mean via ANCOVA. Level of statistical significance (α) was set at .05 for all comparisons and was not adjusted because of the preliminary nature and size of the study.

Role of the Funding Source

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Results

The mean age of the participants was 54.49 years (SD=9.69), and they were at an average of 17.62 months (SD=10.50) after stroke onset. The demographic and clinical characteristics of participants in the 3 groups (Tab. 1) did not differ significantly. Tables 2 and 3 present the descriptive statistics and inferential statistics for the kinematic variables and clinical measures. Two participants in the RBAT group and 1 participant in the CT group did not complete the bimanual task. No adverse events of pain were reported among the participants.

Kinematic Measures

For kinematic variables in the unilateral task, the ANCOVA results revealed significant differences among the 3 groups in NMT ($F_{2,38}$=3.79, *P*=.032, η^2=.17), NMUs ($F_{2,38}$=3.95, *P*=.028, η^2=.17), trunk NTD ($F_{2,38}$=3.82, *P*=.031, η^2=.17), trunk contribution slope for the middle part ($F_{2,38}$=5.51, *P*=.008, η^2=.23), and angular change of shoulder joints ($F_{2,38}$=4.77, *P*=.014, η^2=.20). *Post hoc* analyses revealed that the TBAT group, but not the RBAT group, demonstrated a significant decrease on NMT (*P*=.011), NMUs (*P*=.009), and trunk NTD (*P*=.009) compared with the CT group. Compared with the CT and RBAT groups, the TBAT group produced greater improvements in the trunk contribution slope for the middle part (TBAT group versus RBAT group, *P*=.008; TBAT group versus CT group,

Table 2.
Descriptive and Inferential Statistics for Analysis of Reaching Kinematics[a]

Variable	Pretreatment ($\bar{X}\pm SD$)			Posttreatment ($\bar{X}\pm SD$)			ANCOVA		
	RBAT Group	TBAT Group	CT Group	RBAT Group	TBAT Group	CT Group	F	P	η^2
Unilateral task	(n=14)	(n=14)	(n=14)	(n=14)	(n=14)	(n=14)			
NMT (s/mm)	0.008 (0.0045)	0.008 (0.0058)	0.0065 (0.0049)	0.0078 (0.0049)	0.0054 (0.0025)	0.0081 (0.0042)	3.79	.03[b]	.17
NMUs (unit/mm)	0.043 (0.026)	0.056 (0.064)	0.033 (0.030)	0.046 (0.031)	0.033 (0.029)	0.049 (0.033)	3.95	.03[b]	.17
Trunk NTD (mm/mm)	1.22 (0.18)	1.31 (0.49)	1.58 (1.31)	1.23 (0.21)	1.13 (0.10)	1.52 (0.76)	3.82	.03[b]	.17
Trunk contribution (mm/mm)									
Slope: start	3.21 (4.08)	3.37 (3.35)	2.70 (3.96)	4.94 (5.45)	3.25 (4.47)	5.02 (5.62)	0.59	.56	.03
Slope: mid	2.13 (2.15)	0.96 (1.35)	2.84 (3.75)	1.37 (2.07)	2.93 (3.31)	1.55 (2.30)	5.51	.01[b]	.23
Angular change (°/mm)									
nShoulder flexion	0.16 (0.058)	0.13 (0.034)	0.14 (0.045)	0.19 (0.073)	0.14 (0.025)	0.14 (0.039)	4.77	.01[b]	.20
nElbow extension	0.10 (0.038)	0.061 (0.033)	0.094 (0.039)	0.098 (0.037)	0.078 (0.034)	0.098 (0.053)	0.15	.87	.004
Bimanual task	(n=12)	(n=14)	(n=13)	(n=12)	(n=14)	(n=13)			
NMT (s/mm)	0.0052 (0.0017)	0.007 (0.0032)	0.0059 (0.0044)	0.0048 (0.0014)	0.005 (0.003)	0.0033 (0.0032)	1.70	.20	.09
NMUs (unit/mm)	0.022 (0.009)	0.033 (0.029)	0.037 (0.016)	0.023 (0.012)	0.026 (0.022)	0.048 (0.037)	3.09	.06	.15
Trunk NTD (mm/mm)	1.21 (0.16)	1.51 (0.77)	2.06 (2.35)	1.24 (0.20)	2.35 (3.36)	1.24 (0.35)	1.85	.17	.10
Trunk contribution (mm/mm)									
Slope: start	−0.08 (6.28)	9.15 (13.61)	4.33 (9.34)	1.80 (6.83)	6.90 (9.89)	1.41 (9.75)	0.63	.54	.04
Slope: mid	4.94 (5.11)	4.12 (4.38)	4.70 (6.84)	6.27 (9.61)	8.13 (8.52)	2.12 (4.07)	3.44	.04[b]	.16
Angular change (°/mm)									
nShoulder flexion	0.16 (0.029)	0.12 (0.035)	0.15 (0.063)	0.17 (0.028)	0.12 (0.045)	0.11 (0.064)	4.92	.01[b]	.22
nElbow extension	0.062 (0.039)	0.025 (0.050)	0.048 (0.042)	0.074 (0.039)	0.062 (0.056)	0.049 (0.056)	1.23	.31	.07

[a] ANCOVA=analysis of covariance, RBAT=robot-assisted bilateral arm training, TBAT=therapist-based bilateral arm training, CT=control treatment, NMT=normalized movement time, NMU=normalized movement unit, trunk NTD=normalized trunk displacement, nShoulder flexion=normalized shoulder flexion, nElbow extension=normalized elbow extension.

[b] $P<.05$, $\eta^2=SS_b/SS_{total}$.

$P=.005$). The RBAT group engendered a larger improvement in the angular changes of shoulder flexion than the TBAT and CT groups (RBAT group versus TBAT group, $P=.031$; RBAT group CT group, $P=.005$).

For kinematic variables in the bimanual task, the ANCOVA results showed differences among the 3 groups in trunk contribution slope for the middle part ($F_{2,35}=3.44$, $P=.043$, $\eta^2=.16$) and angular changes of the shoulder joint ($F_{2,35}=4.92$, $P=.013$, $\eta^2=.22$). *Post hoc* analyses revealed that the TBAT group, but not the RBAT group, demonstrated larger enhancement on trunk contribution slope for the middle part ($P=.013$) than the CT group. In addition, higher gains in the angular changes of the shoulder flexion were produced in the RBAT group than in the CT group ($P=.004$).

Clinical Measures

No group effect on the overall FMA score, proximal part score of the FMA, and AOU and QOM of the MAL was documented; however, performance on the distal part of the FMA was significantly different among the 3 groups ($F_{2,38}=3.84$, $P=.03$, $\eta^2=.168$). *Post hoc* analyses revealed that the score for the distal part of the FMA was higher in the TBAT group than in the CT group ($P=.012$). Differences also were found in the SIS total score ($F_{2,38}=4.58$, $P=.017$, $\eta^2=.19$), strength subscale ($F_{2,38}=5.02$, $P=.012$, $\eta^2=.21$), and physical function domain ($F_{2,38}=4.54$, $P=.017$, $\eta^2=.19$). *Post hoc* analyses indicated that the RBAT group showed larger improvement in total score ($P=.005$), strength subscale ($P=.003$), and physical function domain ($P=.005$) of the SIS than the CT group.

Discussion

To our knowledge, this comparative efficacy study is the first to evaluate

Table 3.
Descriptive and Inferential Statistics for Clinical Measures[a]

Variable	Pretreatment ($\bar{X}$±SD)			Posttreatment ($\bar{X}$±SD)			ANCOVA		
	RBAT Group (n=14)	TBAT Group (n=14)	CT Group (n=14)	RBAT Group (n=14)	TBAT Group (n=14)	CT Group (n=14)	$F_{2,38}$	P	η^2
FMA									
Total	43.29 (10.09)	43.43 (10.63)	45.43 (11.42)	47.14 (10.97)	48.71 (10.39)	48.57 (12.32)	1.85	.17	.09
Proximal	31.43 (4.54)	29.57 (5.30)	30.93 (3.93)	33.07 (4.46)	32.14 (4.62)	33.14 (4.31)	0.32	.73	.02
Distal	11.86 (7.05)	13.86 (6.50)	13.40 (7.44)	14.07 (7.66)	16.57 (7.30)	15.43 (9.10)	3.84	.03[b]	.17
MAL									
AOU	0.53 (0.47)	0.68 (0.51)	0.87 (1.00)	0.82 (0.65)	1.03 (0.91)	1.25 (1.25)	0.01	.99	.001
QOM	0.66 (0.51)	0.78 (0.61)	0.97 (1.05)	1.03 (0.79)	1.18 (0.83)	1.59 (1.51)	0.40	.68	.02
SIS									
Total	68.62 (7.62)	64.27 (5.26)	65.23 (11.19)	73.97 (8.68)	67.61 (5.72)	64.75 (12.94)	4.58	.02[b]	.19
Strength	41.52 (9.99)	40.63 (12.91)	37.05 (12.37)	51.34 (14.75)	44.20 (10.53)	36.16 (14.54)	5.02	.01[b]	.21
Memory	91.11 (13.70)	89.28 (7.78)	85.46 (15.18)	93.07 (9.04)	89.27 (9.72)	86.73 (14.72)	0.49	.61	.03
Emotion	59.50 (15.17)	60.72 (12.45)	51.19 (10.49)	60.32 (9.66)	62.31 (12.51)	55.76 (13.38)	0.07	.93	.004
Communication	94.48 (13.01)	90.55 (11.68)	85.97 (18.51)	96.23 (8.67)	94.63 (7.40)	87.23 (14.67)	1.76	.19	.09
ADL/IADL	82.38 (10.50)	74.79 (10.83)	77.77 (12.23)	85.64 (11.81)	73.29 (13.66)	73.50 (17.97)	1.90	.16	.09
Mobility	91.55 (7.93)	83.32 (7.55)	80.16 (17.02)	94.25 (3.98)	86.17 (7.83)	76.40 (23.75)	2.27	.11	.11
Hand function	40.20 (28.78)	34.86 (18.51)	47.86 (25.70)	53.84 (22.50)	48.36 (28.74)	50.57 (27.84)	1.05	.36	.05
Participation	48.23 (20.03)	40.00 (25.50)	56.37 (24.07)	57.09 (28.70)	42.67 (18.60)	51.66 (21.41)	1.08	.35	.05
Physical function	63.91 (11.17)	58.39 (7.07)	60.71 (12.73)	71.27 (9.43)	63.00 (10.07)	59.16 (17.08)	4.54	.02[b]	.19

[a] ANCOVA=analysis of covariance, RBAT=robot-assisted bilateral arm training, TBAT=therapist-based bilateral arm training, CT=control treatment, FMA=Fugl-Meyer Assessment, MAL=Motor Activity Log, AOU=amount of use, QOM=quality of movement, SIS=Stroke Impact Scale, ADL/IADL=activities of daily living/instrumental activities of daily living.
[b] $P<.05$, $\eta^2=SS_b/SS_{total}$.

movement quality, trunk compensation, daily functions, and quality of life of TBAT, RBAT, and CT. Therapist-based BAT and RBAT demonstrated differential benefits on specific outcome measures compared with CT. The TBAT group showed better temporal efficiency (NMT), smoothness (NMUs), and straighter trunk motion (NTD) during the unilateral task than the CT group. The TBAT group also showed less trunk compensation (trunk contribution) than the CT group during the unilateral and bimanual tasks and the RBAT group in the unilateral task. In contrast, the RBAT group demonstrated specific benefits for increasing shoulder flexion (angular changes of shoulder joint) compared with the CT group during the unilateral and bimanual tasks and the TBAT group in the unilateral task. The TBAT group also achieved better performance in the distal part score of the FMA than the CT group, whereas the RBAT group had higher strength subscale, physical function domain, and total scores of the SIS than the CT group.

In general, BAT based on therapist or robot demonstrated superior performance compared with the control intervention. Bilateral arm training seems to contradict the principles of unilateral training, such as constraint-induced therapy, where the movement of the unaffected limb is limited and intensive practice of the affected limb is required. However, BAT and unilateral training, including constraint-induced therapy, share a similar mechanism of rebalanced interhemispheric inhibition and disinhibition. The mechanisms for BAT involve the generation of a "template" by the contralesional hemisphere and the activations in both hemispheres, leading to balanced inhibitory effects between hemispheres.[33] The mechanism for unilateral training (eg, constraint-induced therapy) relates to the facilitation of ipsilesional hemisphere activation, resulting in a disinhibitory effect of the contralesional cortex to the ipsilesional side and, thus, rebalanced activation between the 2 hemispheres.[34]

Benefits of TBAT Over Other Interventions

Generally consistent with a previous study,[8] the TBAT group performed the reaching task more efficiently (less NMT) and smoothly (less NMUs) with the affected arm and with straighter trunk motion (less trunk NTD) in the unilateral task than the CT group. The possible explanation for the superiority of TBAT may have been the KR and KP provided by therapists and the active problem-solving process when functional tasks were practiced. By being provided with KR and KP, participants were able to perceive information about movement outcome and process and make the next attempt more successful by trying to reduce movement errors.[35,36] The feedback thus might have helped facilitate motor learning and lead to better movement quality for patients in the TBAT group. In contrast, the RBAT group practiced only forearm pronation-supination and wrist flexion-extension in passive or active modes provided by the Bi-Manu-Track, which enforced movements in designed and suitable trajectories. Participants in the RBAT group lacked patient-therapist interaction and experience in error-based learning in functional tasks, which did not lead to superior effects on arm and trunk performance.

The TBAT group recruited less trunk involvement (greater value of trunk contribution slope for the middle part) than the RBAT and CT groups during unilateral reaching and the CT group during the bilateral reaching task. When both arms perform a similar spatiotemporal pattern simultaneously, the "template" generated by the undamaged hemisphere may provide normal motor plans (ie, reaching with minimal trunk displacement)[2] to assist in restoring the movement pattern of the hemiplegic UL.[33] Moreover, the motor system organizes the trunk and proximal part musculature of the UL on a bilateral basis.[37] The functional tasks in the TBAT group involved ULs without constraining the trunk and then provided more opportunities to practice arm-trunk coordination while performing the tasks. In contrast, the tasks in RBAT involved minimal trunk movement via the static position of both arms strapped to the Bi-Manu-Track, which offered less arm-trunk coordination than TBAT. Consequently, TBAT may better facilitate trunk-limb organization in a desirable or normal way and lead to fewer trunk compensatory movements than RBAT.

The TBAT group improved arm and trunk movement quality only in the unilateral task, which might be explained by the nature of the tasks. Participants were asked to perform the unilateral task as fast as possible but to execute the bimanual task with comfortable self-speed, which may not have been sensitive enough to induce differences among the 3 groups. Moreover, the bimanual task used in this study (eg, pull a drawer with the affected hand and retrieve an eyeglass case with unaffected hand) involved bilateral, sequential reaching that was different from the bilateral, simultaneous movements practiced in TBAT.

Partially consistent with a previous study,[7] the TBAT group produced greater improvements in the distal part score of the FMA, but not in the overall and proximal part of the FMA. Simultaneously moving both arms may have rebalanced interhemispheric activation and inhibition,[38] thus reducing the distal part of motor impairment of the affected UL.[4,39,40] Furthermore, consistent with previous research,[41,42] this study demonstrated no significant differences among the groups in daily functions as measured by the MAL. This result might be because the bilateral symmetrical activities of the TBAT program did not emphasize forced use of the affected UL. Most bimanual tasks in daily life require bilateral sequential movement, but not bilateral simultaneous movement.[4] Therefore, practice of bilateral symmetric activities might not be able to incorporate gain in the distal part of motor function into daily use of the affected UL.

Benefits of RBAT Over Other Interventions

The RBAT group had larger improvements in angular changes of shoulder flexion compared with the TBAT and CT groups in unilateral reaching and with the CT group in bimanual reaching. The Bi-Manu-Track robot provides robot-assisted, distal movement training, characterized by a constant velocity and a high number of repetitions in passive or active mode, which reestablishes the normative movement pattern by increasing the quality and quantity of sensorimotor information.[43] Thus, the range of motion was improved. The distal movement training provided by the Bi-Manu-Track in the present study demonstrated treatment effects on the proximal part of the UL such as shoulder joints. The distal approach may lead to a stronger activation in the sensorimotor cortex, given the larger cortical representation, than the proximal training and thus result in benefits to the proximal joints.[6] Another explanation for the possible advantages may be that the proximal parts also were working intensely during distal training.[15] Interestingly, the 3 groups differed significantly in shoulder flexion but not in elbow extension range of motion. Voluntary elbow extension is less amenable to change than shoulder flexion.[44] It is difficult to generate elbow extension in the affected limb when reaching outward[45] because of the strong synergistic joint torque coupling of shoulder abductor and elbow flexion.[46–48]

Direct comparisons between bilateral protocols of the present study and unilateral protocols of the previous studies[49,50] might be arguable. A previous study[50] suggested that intensive unilateral arm training mediated by a therapist or a robot improved motor impairment of the proximal UL, but not motor function and quality of life. In contrast, another study[49] showed that intensive, robot-assisted, unilateral therapy significantly improved quality of life, but not motor function, immediately after intervention compared with conventional intervention. Differences in the intensity of training and the type of robot may explain the differential effect in these 2 studies. Our study extended the study findings of Lo et al[49] and showed that the group who underwent robot-assisted training based on a bilateral protocol had larger gains in quality of life, as reflected by the strength subscale, physical function domain, and total score of the SIS, than the CT group. Even though our study recruited participants with moderate-to-mild UL impairment and used bilateral protocols different from those of the study by Lo et al[49] using patients with moderate-to-severe UL impairment and treatment approaches with unilateral protocols, both studies adopted intensive, robot-assisted therapy to enhance quality of life for patients with chronic stroke.

In contrast, Volpe et al[50] did not find significant changes in SIS scores after using a different robot (InMotion2 [Interactive Motion Technology Inc, Cambridge, Massachusetts], the commercial version of MIT-MANUS) for less intensive training (1 hour per session, 3 times a week for 6 weeks). The RBAT in this study involved moving the distal bilateral arm against initial resistance in mode 3 (ie, active-active), which is similar to a strength training program and, therefore, may enhance strength output. Accordingly, patients who receive RBAT may report higher quality of life in the strength subscale than those who receive CT. Moreover, distal paretic limb strength has a strong relationship with daily activity, and strength-related training might have enhanced the UL performance in daily living in individuals with chronic stroke.[51,52] Robot-assisted BAT increases active range of motion, as evidenced in the present study, and possibly decreases spasticity of the wrist and forearm.[43] It follows that improved physical conditions (self-perceived muscle strength and quantitative measures of range of motion) in daily living might lead to better perception of the physical function domain and overall quality of life.[43]

A limitation of this study was the lack of a follow-up assessment, which may limit the understanding of potential long-term benefits. Future research should examine the retention of therapeutic gains after TBAT and RBAT. In addition, appropriate methods for measuring real-world activity are a concern.[53] The MAL exclusively measures the functional performance of the affected UL, which may not be the most suitable one for assessing the outcomes after bilateral training protocols. Future studies need to assess changes on outcome measures relevant to patients' daily situations, including bilateral tasks (eg, the ABILHAND questionnaire,[54] accelerometry[55]) for monitoring activity of the ULs in the community. Finally, the significant results should be considered with caution, as correction for multiple comparisons was not done due to the preliminary nature and size of the study.

Conclusions

This is the first study to compare bilateral arm training mediated by a therapist versus a robot in improving motor control, functional performance, and quality of life in patients with stroke. These findings suggest that TBAT might uniquely improve temporal efficiency, smoothness, and trunk compensation of reaching movement and motor impairment of the distal part of the UL. Robot-assisted BAT may be a more compelling approach to improve shoulder flexion range of motion and quality of life related to paretic UL function.

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The institutional review boards of the participating sites approved this study.

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