

Alterations in muscle activation patterns during robot-assisted bilateral training: A pilot study

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Abstract

Robot-assisted bilateral training is being developed as a new rehabilitation approach for stroke patients. However, there is still a lack of understanding of muscle functions when performing robot-assisted synchronous movements. The aim of this work is to explore the muscle activation patterns and the voluntary effort of participants during different robot-assisted bilateral training protocols. To this end, 10 healthy participants were recruited to take part in a 60-minute experiment. The experiment included two different bilateral exercises, and each exercise contained four different training protocols. Trajectories of the robots, interaction force and surface electromyogram signals were recorded during training. The results show that the robots do affect the muscle activation patterns during different training protocols and exercises rather than the controller. Specifically, the activity of muscles is reduced in robot-assisted training but is increased in active force involved robot-assisted training when compared to robot-unassisted training. Meanwhile, the voluntary effort of participants can be presented by the adjusted trajectories via the controller. In addition, the results also suggest that the activations for the same muscle groups in the left and right arms are highly correlated with each other in both exercises. Furthermore, the training protocols and methods developed in this work could be further extended in future clinical trials to investigate therapeutic outcomes for patients as well as to better understand bilateral recovery processes.

Keywords

Robot-assisted bilateral training, muscle activation patterns, surface electromyogram signals, voluntary effort, adaptive admittance controller

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Introduction

Compared to manual training, robot-assisted training can alleviate backbreaking manual work in conventional rehabilitation training and provide precise repetitive training in a sufficiently long time frame.^{1,2} To date, the reliability and validity of robot-assisted training have been verified by many clinical trials.³ The most utilized motion types in robot-assisted training are (1) continuous passive motion, (2) active-assisted motion and (3) active-resisted motion.⁴ According to Volpe et al.,⁵ voluntary effort involved motion, including active-assisted motion and active-resisted motion, is more effective on motor functional improvement than continuous passive motion. The main rationale is that stroke patients in these motions are encouraged to try self-initiated movement, which is essential for provoking brain plasticity and motor learning.^{6–8} Voluntary

effort can also show the physical conditions of stroke patients via active force according to the Brunnstrom approach⁹ and muscle strength grading,¹⁰ since different recovery stages of stroke have different grades of muscle strength. Therefore, voluntary effort is

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important for stroke rehabilitation,⁸ which can be represented by active force and surface electromyogram (sEMG) signals.

Moreover, muscle responses to different training protocols (with or without robots, or different motions) are important for stroke rehabilitation as well, which is the foundation for developing rehabilitation robots, control strategies and training protocols.¹¹ Using rehabilitation robots to explore the activation correlations of different muscles is also helpful in order to understand the cooperation mechanism of each pair of muscles under different training protocols, and further, to evaluate the effectiveness of robot-assisted training protocols.¹² To date, muscle activation patterns have been researched and reported in literature; however, most of them were related to the lower limbs rather than upper limbs. Two studies^{11,13} reported the activity patterns of leg muscles during different robot-assisted walking conditions. The experimental results showed that the Lokomat did negatively influence the muscle activation patterns due to its limitations. Even though the findings were not identical to their hypotheses, they still can contribute to the understanding of human-machine interactions. Three other studies¹⁴⁻¹⁶ mentioned the muscle activation patterns of upper limbs under robot-assisted training, however, these patterns were used as the indexes to evaluate their rehabilitation robots or training protocols, rather than to explore the cooperation mechanism of each pair of muscles during different training protocols.

Recently, bilateral rehabilitation training was proposed based on the report that the activation of the damaged hemisphere can be promoted by the activation of the undamaged hemisphere. This was facilitated through a simultaneous movement with the most affected arm and the less affected arm.^{17,18} Bilateral training can also enhance patients' body coordination, which cannot be trained via traditional unilateral training, for example, holding a ball or twisting a towel. To date, several robotic systems have been developed or revised for bilateral training, and experimental results support the suggestion that bilateral training is at least as effective as unilateral training for stroke rehabilitation.¹⁹ However, to the best of the authors' knowledge, studies that focus on the voluntary effort and muscle activation patterns during robot-assisted bilateral training have rarely been reported. In addition, as discussed above, research related to the muscle activation patterns of upper limbs is also limited.

Therefore, the main purpose of this work is to investigate the voluntary effort and upper-limb muscle activation patterns of healthy participants during different robot-assisted bilateral training protocols. The activation correlations of different muscles are also explored within one arm and between two arms to establish a set of "standard" criteria. The criteria could then be utilized as a baseline to assess the patterns exhibited by stroke patients through the same bilateral rehabilitation system and training protocols in the future. It is

hypothesized that for healthy participants, the activity of the arm muscles would be the same as the leg muscles, specifically, the arm muscles would be reduced to a lower level in a robot-assisted training compared to a robot-unassisted training.^{11,13} The rest of the article is organized as follows: 'Methods' section illustrates the methods for this work; 'Results' section describes the results of two different bilateral training protocols; 'Discussion' section presents the discussion, followed by the conclusion in the 'Conclusion' section.

Methods

The bilateral rehabilitation system

The utilized system contains two universal robots (URs; UR5 and UR10, Universal Robots A/S, Denmark), two 6-axis load cells (SRI M3713 C and SRI M3715 C, Sunrise Instruments Co., Ltd, China), two customized handle bars, one computer and one network switch (Figure 1).²⁰ The UR robot comprises one UR control box and one UR arm. The UR arm is a six-DOF motor-operated robot manipulator, which guarantees the intrinsic compliance during training and allows participants to move their arms in three-dimensional (3D) space with a large range of motion (ROM). Real-time interaction force between participants and robots is measured by the load cells installed below the customized handle bars, which makes precisely controlled bilateral training possible. The final design of the handle bar includes a supporter for participants' hands and wrists as well as Velcro straps to fix participants' hands with a grip, which enables the affected limbs of participants to use the device.

An adaptive admittance controller proposed in a previous study²⁰ is utilized in our work for two purposes. The main purpose is based on the "subject-centered" concept, that is, participants can adjust trajectories through their own force rather than strictly follow reference trajectories, and thus their voluntary efforts can be reflected in the adjusted trajectories. At the same time, participants can have a higher level of engagement for bilateral training. The other purpose is to improve the robustness of training by reducing disturbances from participants, devices, or external environment, as well as the time-delay between two robots, which is the foundation for precisely controlled bilateral training.

Furthermore, a series of safety measures are also implemented in both software and hardware. Researchers could terminate two robots with a stop command through the software at the same time. The UR robot would stop automatically if movements reach safety boundaries (± 500 mm for x axis, ± 600 mm for y axis and ± 350 mm for z axis), or velocity, acceleration or interaction force of the robots exceed risk thresholds. The robots could also be shut down by cutting off the power through emergency buttons by researchers and participants at all times.

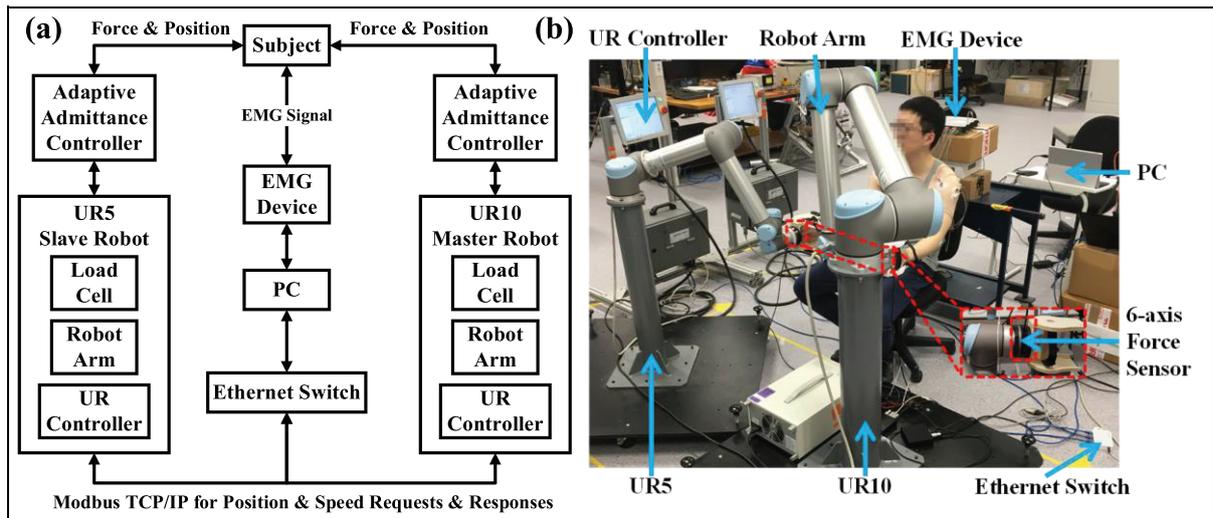


Figure 1. The proposed bilateral rehabilitation system: (a) the block diagram of the system and (b) a healthy participant with the system.

Table 1. The demographics of the participants.

Participant	Gender	Age (years)	Height (cm)	Weight (kg)	BMI (kg/m ²)
1	Male	29	186	85	24.6
2	Male	29	172	60	20.3
3	Male	27	182	72	21.7
4	Male	28	175	70	22.9
5	Male	26	168	58	20.5
6	Male	26	180	85	26.2
7	Male	28	181	83	25.3
8	Male	29	183	69	20.6
9	Male	29	183	90	26.9
10	Male	28	176	67	21.6
Mean		27.9	178.6	73.9	23.1
SD		1.1	5.4	10.6	2.4

BMI: body mass index.

Participants

Ten healthy male participants (mean age: 27.9 ± 1.14 years, height: 178.6 ± 5.37 cm, weight: 73.9 ± 10.61 kg and body mass index (BMI): 23.1 ± 2.37 kg/m²) were recruited in our work. The demographics of the participants can be seen in Table 1. Participants had no known nervous system diseases or upper-limb disorders. Other physical preparations were the same as other research,²¹ for example, avoiding strenuous exercises for the 24^{hr} prior to experiment. All experimental procedures were approved by the University of Auckland Human Participants Ethics Committee (reference 015256).

Experiment protocol

The flowchart of the experiment protocol has been shown in Figure 2(a). Before the experiment, each participant was invited to do an evaluation to assess his physical condition for this experiment. If they passed the evaluation, they were instructed on how to

terminate the robots and the sEMG collection when emergencies occurred such as mechanical failures or skin allergies. After that, they were given a brief demonstration of the rehabilitation training device, and their age, gender, height, weight and other information were collected and the participant consent form was signed as well.

After the evaluation, explanation and consent collection, disposable Ag-AgCl electrodes (3M Red Dot, 3M Health Care, Germany) were placed in pairs over the skin with an interelectrode spacing of 0.02 m.²² Prior to sEMG electrode placement, skin was shaved of hair if necessary and vigorously cleansed with alcohol wipes until erythema was attained.²³ The sEMG electrodes were then placed along the main direction of muscle fibers based on the suggestions by SENIAM (the European project on sEMG).²² The wires of the electrodes were wrapped with ace bandages to ensure that they did not impede movements. Eight muscles of the left and right arms of each participant were selected, including left biceps brachii (LBB), left anterior deltoid

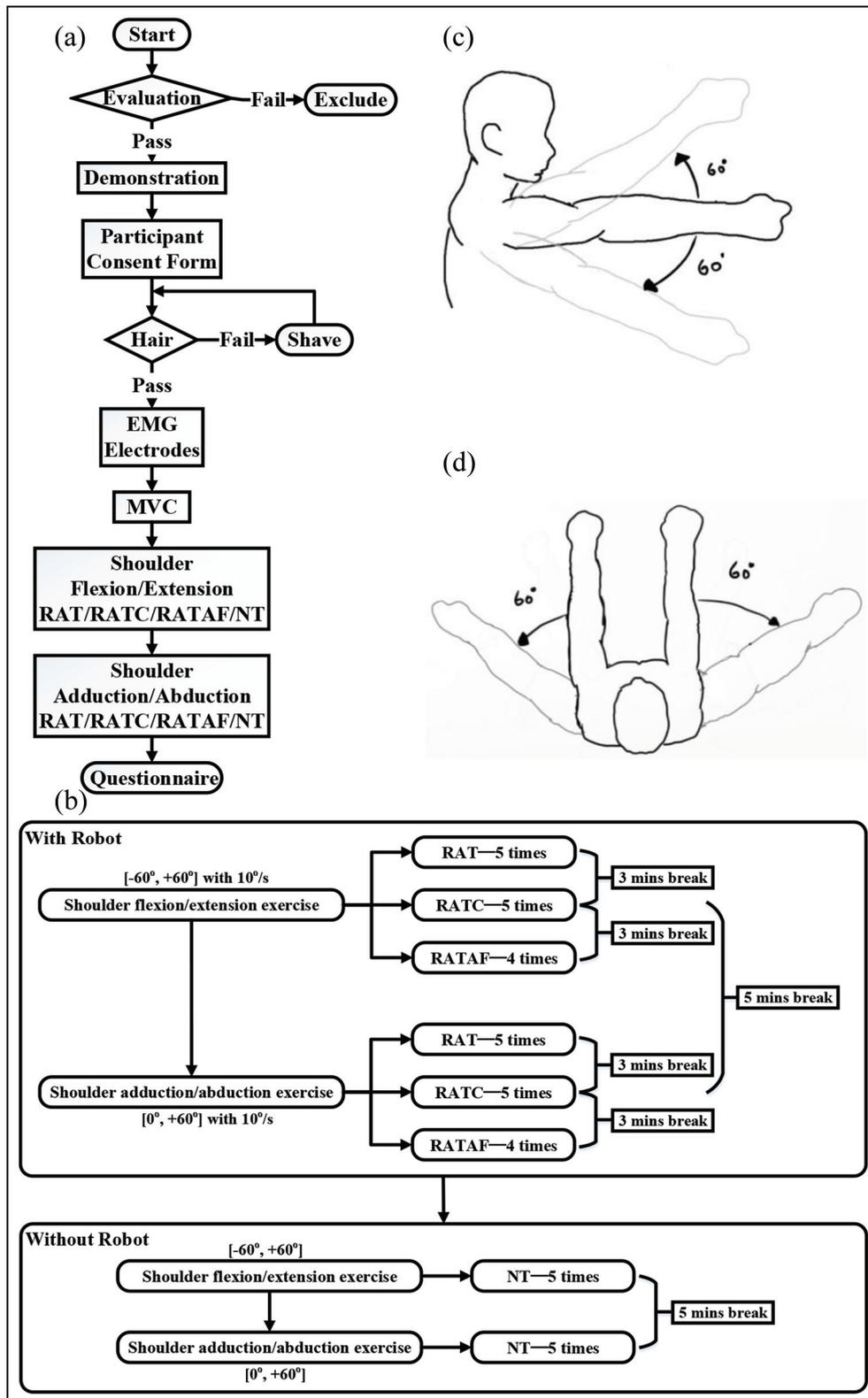


Figure 2. The detailed information of the experimental design: (a) the flowchart of the experiment protocol, (b) the flow diagram of the training protocol, (c) shoulder flexion/extension exercise and (d) shoulder adduction/abduction exercise.

RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training; EMG: electromyogram; MVC: maximum voluntary contraction.

(LAD), left lateral deltoid (LLD), left posterior deltoid (LPD), right biceps brachii (RBB), right anterior deltoid (RAD), right lateral deltoid (RLD) and right

posterior deltoid (RPD). After being fully instrumented, each participant was asked to do a maximum voluntary contraction (MVC) for eight muscles. Finally,

they were invited to sit on an adjustable chair and grasp the handle bar attached to the robots to perform the experiment (Figure 1(b)).

After analyzing²⁴ and a guide from the National Stroke Association, two exercises were selected for this work. Each exercise contained three robot-assisted training protocols with randomized orders: RAT, RATC and RATAF. “RAT” referred to the robot-assisted trajectory training, “RATC” referred to the robot-assisted trajectory training with the controller and “RATAF” referred to the robot-assisted trajectory training with active force. For the first exercise, the arms of participants were passively moved by the robots along a predefined trajectory: shoulder flexion/extension with the range of $[-60^\circ, +60^\circ]$ at a speed of $10^\circ/\text{s}$ (Figure 2(c), henceforth named flexion/extension exercise).²⁵ Participants were trained 5 times for RAT/RATC and 4 times for RATAF, so the total training time was around 6 min. In order to avoid muscle fatigue, 3-minute break after each training and 5-minute break after each exercise were performed as well. For the second exercise, the basic training protocol was similar to the first exercise, except the predefined shoulder trajectory was changed to horizontal adduction/abduction with the range of $[0^\circ, +60^\circ]$ and at the same speed.²⁴ Therefore, the total training time in the second exercise was around 5 min with the same break (Figure 2(d), henceforth, named adduction/abduction exercise). Meanwhile, after finishing robot-assisted training, each participant was asked to repeat the same training protocol without the robots, which was treated as the normal training (henceforth, named NT). In this training protocol, participants did the same movements as described above; the total training time was diverse but the 5 min break after each exercise was the same. During the training, two angular sheets were attached to each participant to make sure that the motion ranges were the same as $[-60^\circ, +60^\circ]$ and $[0^\circ, +60^\circ]$ for the flexion/extension and the adduction/abduction exercises, respectively (The flow diagram of the training protocol can be seen in Figure 2(b)). After completing all the exercises, a questionnaire was completed by each participant to evaluate the bilateral rehabilitation system, the controller and the training protocols. The total training time for the experiment was around 1^h including acclimation stages.

It can be seen from Table 2 that the main differences between four different training protocols were: in RAT, participants followed trajectories provided by the robots without the controller; in RATC, participants still followed the trajectories but the controller was used for each robot; in RATAF, participants followed the same trajectories with the same controller in RATC for the first and fourth rounds, but they were asked to adjust the trajectories in the second and third rounds through active force; in NT, participants moved freely without the robots. The main objectives for doing these four training protocols were (1) to explore the sEMG patterns of the controller involved/uninvolved training

Table 2. Components involved in each training.

Training name	Involvement		
	Robot	Controller	Active force
RAT	√	×	×
RATC	√	√	×
RATAF	√	√	√
NT	×	×	×

RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training.

protocols under robot-assisted trajectories (RATC to RAT), (2) to explore the sEMG patterns of the active force involved/uninvolved training protocols under robot-assisted trajectories (RATAF to RATC), (3) to explore the sEMG patterns of the robots involved/uninvolved training protocols (RAT, RATC and RATAF to NT) and (4) to explore the activation correlations of each pair of muscles under different training protocols and different exercises. Note that all the training protocols were bilateral.

Data reduction and analysis

In robot-assisted training protocols, force was recorded by 6-axis load cells at 50 Hz, which was the same sampling frequency of moving trajectories recorded by the robot systems.²² Raw sEMG signals were collected with a g.USBamp at a sampling frequency of 1200 Hz (24-bit biosignal amplification unit, g.tec Medical Engineering GmbH, Austria), which were all antialias filtered.¹³ After that, the linear envelope of sEMG signals was obtained by (1) a second-order high-pass Butterworth filter with a cut-off frequency at 20 Hz, (2) a full-wave rectification, (3) a fourth-order low-pass Butterworth filter with a cut-off frequency at 4 Hz and (4) normalized by dividing peaks with the MVC.²²

In order to compute ensemble-averaged sEMG waveforms, processed sEMG linear envelopes were divided by each round and then averaged. Final results were expressed by the angular variation for each muscle: for the flexion/extension exercise, the results were shown by $[-60^\circ, +60^\circ]$; for the adduction/abduction exercise, the results were shown by $[0^\circ, +60^\circ]$. The activations of muscles were expressed by an ensemble-averaged sEMG graph as well as mean and max sEMG activity histograms. Black bars were placed on the left side of the ensemble-averaged sEMG graph to show the activity levels of muscles appropriately. Note that all the participants were male thus avoiding the influence of gender. All the participants were postgraduate students (between 26 and 29 years old, young adult stage), and the standard deviation (SD) of age is 1.13, thus avoiding the influence of age as well. As for the influence of physical characteristics, the measured sEMG data would be normalized by MVC to avoid individual differences, which is the common method to

process sEMG data.²⁶ Therefore, all the processed sEMG signals have the unit of %MVC.

Statistical analysis

Experimental data were tested for normality using the Shapiro–Wilk test. Descriptive statistics contained means \pm SD of mean and max sEMG amplitudes, which were calculated and compared across four conditions (RAT, RATC, RATAF and NT) by one-way analysis of variance (ANOVA) with Bonferroni post hoc test.¹¹ Moreover, Pearson correlation coefficients were calculated to figure out bilateral activation correlations of each pair of muscles in different training protocols.^{11,12} One-sample *t* test was used for comparison of Pearson correlation coefficients at the same time. The statistical significant level was 0.05.

Results

The results are represented in three aspects: (1) the general observations, (2) the influences of controller and robot on sEMG activity and (3) muscle activation correlations. It should be noted that these results are based on male postgraduate students with no known nervous system diseases or upper-limb disorders.

General observations

Figures 3(a) and 4(a) illustrate the ensemble-averaged sEMG patterns of upper-limb muscles in the healthy participants under different training protocols and exercises. In general, the amplitude of sEMG activity in the robot-assisted training with active force (RATAF) is significantly greater than those in robot-assisted training protocols without active force (RAT and RATC), but almost the same as those in robot-unassisted training (NT). Specifically, for the flexion/extension exercise, sEMG waveforms are different in BBs (BBs includes LBB and RBB and so on): in RAT, RATC and NT, there is almost no activity of these two muscles, while the peaks of other muscles occur around a 60° angle; in RATAF, the peaks of BBs' waveforms coincide with the timing of active force applied by the participants. The other finding in RATAF is that PDs (PDs includes LPD and RPD and so on) present additional strenuous fluctuations around a -30° angle when compared to other muscles. As for the adduction/abduction exercise, the mean activity in RATAF is larger for BBs and PDs, while it is comparable for LDs (LDs includes LLD and RLD and so on) and smaller for ADs (ADs includes LAD and RAD and so on) when compared to those in NT. Moreover, BBs and ADs do not present obvious peaks in almost all the training protocols.

Influences of controller and robot on sEMG activity

The influence of the controller, which can be reflected by the magnitude of sEMG activity across different

training protocols, is examined. The activity levels of muscles in RAT are almost the same as those of RATC in both mean and max sEMG activity, and the statistical analysis confirms that no significant difference is observed between these two training protocols (Figures 3(b), 4(b) and 3(c), 4(c)). The influence of the robots is also examined, but due to significant differences between RAT/RATC and NT, RATAF is chosen to compare with NT to explore more findings. In the flexion/extension exercise, the max sEMG activity shows that most muscles' activity levels are higher during RATAF, when compared to those of NT, except LDs (Figure 3(c)). The mean sEMG activity reveals the opposite: only BBs' activity levels in RATAF are higher than those of NT (Figure 3(b)). Statistically significant differences are also found between RATAF and NT. Post hoc multiple comparisons using the Bonferroni test indicate that in the max sEMG activity, BBs in RATAF are significantly different from those in NT. In the mean sEMG activity, ADs and LDs in RATAF are significantly different from those in NT for the same test. In the adduction/abduction exercise, PDs show a higher activity level in RATAF when compared to NT in the mean sEMG activity (Figure 4(b)). In the max sEMG activity (Figure 4(c)), BBs, LDs and PDs present higher activity levels in RATAF when compared to NT.

Muscle activation correlations

The muscle activation correlations are revealed by the results of Pearson correlation coefficients (Tables 3 and 4). Generally, a situation found in almost all the training protocols is that a specific muscle indicates a very strong correlation to the same muscle of the contralateral arm, especially in RATAF.²⁷ In particular, ADs and LDs (LAD to RAD, and LLD to RLD) achieve the strongest correlation coefficient in each training in the flexion/extension and the adduction/abduction exercises, respectively. One interesting finding is that in the adduction/abduction exercise, negative results are observed in RAT, RATC and NT, which means that the activation level of one muscle tends to increase as that of the contralateral muscle tends to decrease. This causes most results in Table 4 to be smaller than those in the flexion/extension exercise (Table 3), and only a few results are significantly different from zero (one-sample *t* test).

Discussion

The comparison of muscle activation patterns demonstrates that significant differences occur in most muscles of upper limbs during both exercises. Meanwhile, some muscle activation correlations during bilateral training are also unveiled.

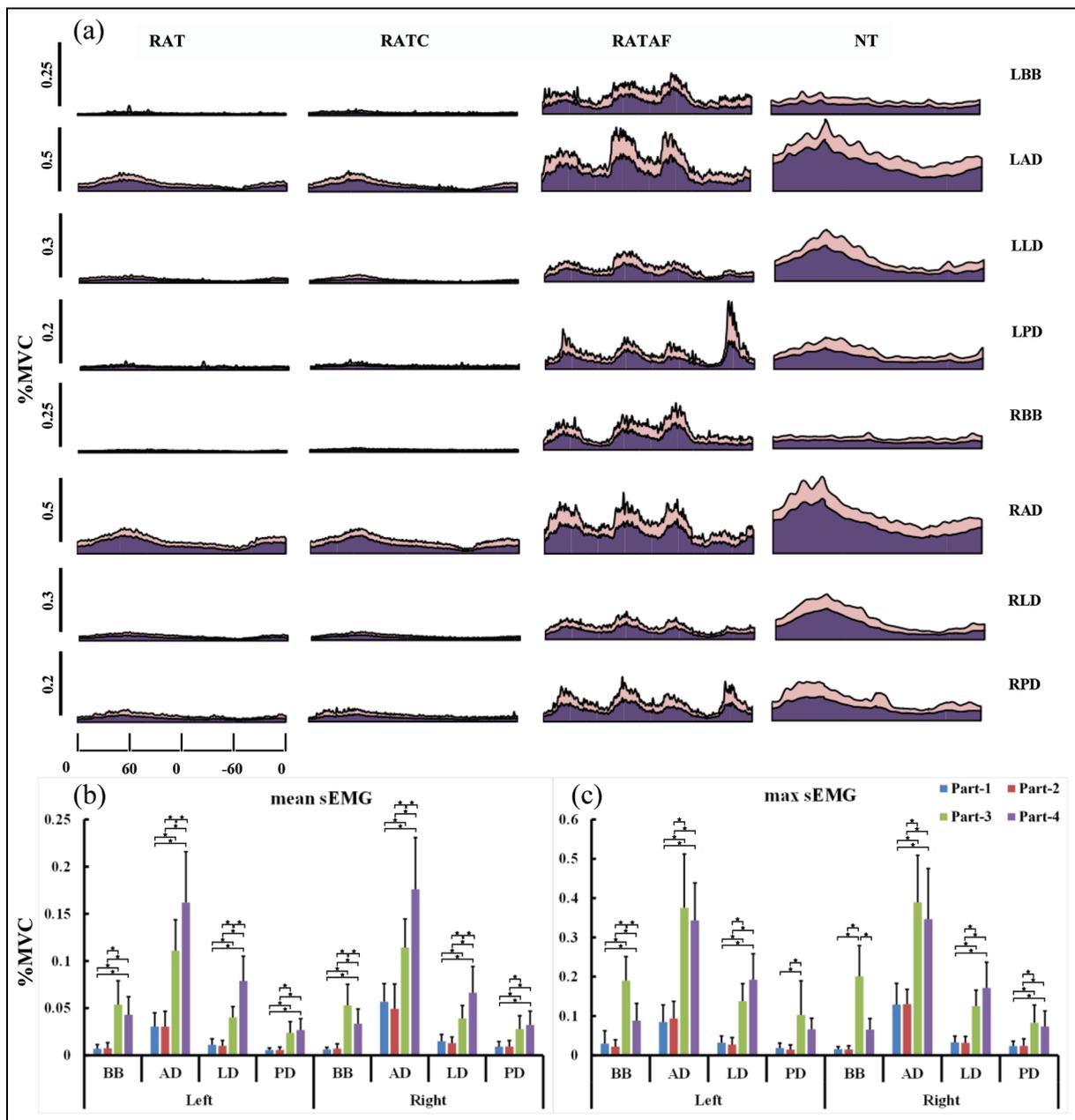


Figure 3. sEMG patterns in shoulder flexion/extension exercise: (a) ensemble-averaged sEMG patterns ($M + SD$, $n = 10$, dark area corresponds to mean, light area corresponds to SD), (b) mean sEMG activity for each muscle and (c) max sEMG activity for each muscle.

sEMG: surface electromyogram; RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training; LBB: left biceps brachii; LAD: left anterior deltoid; LLD: left lateral deltoid; LPD: left posterior deltoid; RBB: right biceps brachii; RAD: right anterior deltoid; RLD: right lateral deltoid; RPD: right posterior deltoid.

*denotes significant difference ($p < .05$ or less).

General muscle activation patterns

In this work, the similarities and differences of healthy participants' muscle activation patterns are investigated via an analysis of the sEMG activity level. During robot-assisted training protocols (RAT and RATC), the bilateral rehabilitation system provides the necessary force to support and guide the participants' arms to follow a reference trajectory (RT). While during a robot-unassisted training (NT), the weight of the upper

limbs have to be borne by the participants throughout the movements without robotic assistance. Therefore, it is understandable that the amplitude of sEMG activity is obviously larger during the robot-unassisted training, when compared to the robot-assisted training. The finding is in broad agreement with similar prior research.^{11,13,28,29} For example, in Hidler and Wall,¹³ the muscle activity of ankle flexor and extensor was reduced during most of the gait cycle with robotic assistance. However, one research¹¹ reported an interesting

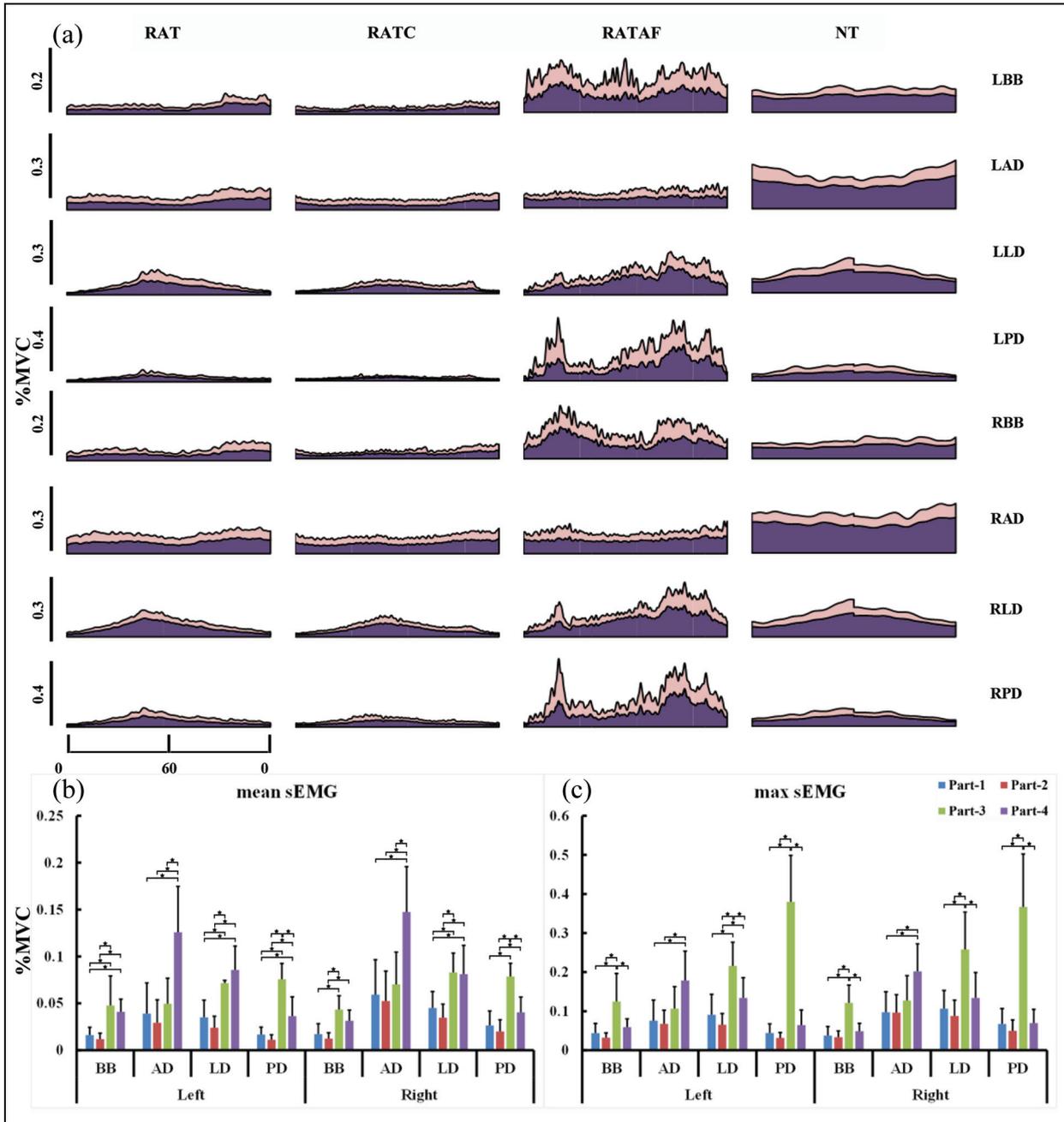


Figure 4. sEMG patterns in shoulder horizontal adduction/abduction exercise: (a) ensemble-averaged sEMG patterns ($M + SD$, $n = 10$, dark area corresponds to mean, light area corresponds to SD), (b) mean sEMG activity for each muscle and (c) max sEMG activity for each muscle.

sEMG: surface electromyogram; RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training; LBB: left biceps brachii; LAD: left anterior deltoid; LLD: left lateral deltoid; LPD: left posterior deltoid; RBB: right biceps brachii; RAD: right anterior deltoid; RLD: right lateral deltoid; RPD: right posterior deltoid.

*denotes significant difference ($p < .05$ or less).

result that the sEMG activity of leg muscles was similar or even larger during robot-assisted walking compared to normal walking, which was in conflict with its hypothesis. The possible reason explained by its authors could be the intermittent contact between the robot and the participant, which can be treated as disturbances to the participant. As for RATAF, one purpose is to explore sEMG activity levels of muscles in

the active force involved robot-assisted training to get a precise participation level. Researchers can also get a better understanding of the impact of participants' voluntary efforts, therefore, adjust training protocols accordingly. A similar procedure has been reported by Yoshida et al.,³⁰ where 3D gait analysis was used to evaluate treatment plans for children with cerebral palsy. Doctors were able to improve the success rate of

Table 3. Pearson correlation coefficients (mean \pm SD, n = 10) for different training protocols in the flexion/extension exercise (bilateral).

Training	Muscle	RBB	RAD	RLD	RPD
RAT	LBB	0.58 \pm 0.27*	0.48 \pm 0.30*	0.49 \pm 0.26*	0.49 \pm 0.27*
	LAD	0.51 \pm 0.25*	0.79 \pm 0.20*	0.74 \pm 0.19*	0.64 \pm 0.26*
	LLD	0.54 \pm 0.24*	0.68 \pm 0.22*	0.74 \pm 0.18*	0.63 \pm 0.24*
RATC	LPD	0.41 \pm 0.24*	0.53 \pm 0.29*	0.60 \pm 0.28*	0.66 \pm 0.32*
	LBB	0.44 \pm 0.20*	0.50 \pm 0.25*	0.50 \pm 0.21*	0.52 \pm 0.23*
	LAD	0.53 \pm 0.14*	0.88 \pm 0.08*	0.85 \pm 0.08*	0.72 \pm 0.24*
RATAF	LLD	0.54 \pm 0.17*	0.79 \pm 0.16*	0.83 \pm 0.08*	0.74 \pm 0.20*
	LPD	0.42 \pm 0.30*	0.55 \pm 0.35*	0.58 \pm 0.35*	0.64 \pm 0.34*
	LBB	0.85 \pm 0.16*	0.75 \pm 0.10*	0.75 \pm 0.08*	0.52 \pm 0.15*
NT	LAD	0.76 \pm 0.19*	0.91 \pm 0.05*	0.85 \pm 0.07*	0.55 \pm 0.22*
	LLD	0.70 \pm 0.24*	0.83 \pm 0.10*	0.89 \pm 0.06*	0.73 \pm 0.17*
	LPD	0.37 \pm 0.28*	0.38 \pm 0.33*	0.58 \pm 0.24*	0.79 \pm 0.12*
NT	LBB	0.64 \pm 0.19*	0.57 \pm 0.25*	0.56 \pm 0.25*	0.55 \pm 0.22*
	LAD	0.52 \pm 0.25*	0.91 \pm 0.08*	0.86 \pm 0.08*	0.80 \pm 0.16*
	LLD	0.53 \pm 0.30*	0.82 \pm 0.14*	0.87 \pm 0.09*	0.80 \pm 0.21*
	LPD	0.55 \pm 0.29*	0.75 \pm 0.20*	0.79 \pm 0.27*	0.80 \pm 0.19*

RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training; LBB = left biceps brachii; LAD: left anterior deltoid; LLD: left lateral deltoid; LPD: left posterior deltoid; RBB: right biceps brachii; RAD: right anterior deltoid; RLD: right lateral deltoid; RPD: right posterior deltoid.

*denotes correlation coefficient significantly different from zero, t test (very weak (.00–.19), weak (.20–.39), moderate (.40–.59), strong (.60–.79) and very strong (.80–1.0))²⁶.

Table 4. Pearson correlation coefficients (mean \pm SD, n = 10) for different training protocols in the adduction/abduction exercise (bilateral).

Training	Muscle	RBB	RAD	RLD	RPD
RAT	LBB	0.51 \pm 0.39*	0.45 \pm 0.34*	–0.27 \pm 0.40	–0.22 \pm 0.41
	LAD	0.45 \pm 0.32*	0.51 \pm 0.44*	–0.33 \pm 0.59	–0.27 \pm 0.60
	LLD	–0.12 \pm 0.52	–0.06 \pm 0.60	0.92 \pm 0.07*	0.86 \pm 0.14*
RATC	LPD	–0.16 \pm 0.50	–0.02 \pm 0.59	0.90 \pm 0.04*	0.88 \pm 0.12*
	LBB	0.58 \pm 0.21*	0.41 \pm 0.25*	–0.01 \pm 0.45	–0.01 \pm 0.37
	LAD	0.37 \pm 0.37*	0.44 \pm 0.48*	–0.14 \pm 0.50	–0.15 \pm 0.44
RATAF	LLD	0.13 \pm 0.48	0.08 \pm 0.51	0.88 \pm 0.09*	0.83 \pm 0.18*
	LPD	0.13 \pm 0.42	0.05 \pm 0.48	0.84 \pm 0.11*	0.83 \pm 0.16*
	LBB	0.73 \pm 0.17*	0.11 \pm 0.44	0.15 \pm 0.41	0.31 \pm 0.30*
NT	LAD	0.03 \pm 0.36	0.51 \pm 0.30*	0.07 \pm 0.47	0.10 \pm 0.38
	LLD	0.04 \pm 0.39	0.25 \pm 0.46	0.87 \pm 0.13*	0.75 \pm 0.18*
	LPD	0.15 \pm 0.37	0.26 \pm 0.40	0.78 \pm 0.25*	0.87 \pm 0.15*
NT	LBB	0.30 \pm 0.28*	–0.16 \pm 0.27	0.15 \pm 0.40	0.14 \pm 0.45
	LAD	0.25 \pm 0.36	0.44 \pm 0.26*	–0.38 \pm 0.37*	–0.43 \pm 0.32*
	LLD	0.14 \pm 0.45	–0.44 \pm 0.30*	0.79 \pm 0.17*	0.77 \pm 0.14*
	LPD	0.04 \pm 0.40	–0.42 \pm 0.33*	0.72 \pm 0.14*	0.78 \pm 0.10*

RAT: robot-assisted trajectory training; RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force; NT: normal training; LBB: left biceps brachii; LAD: left anterior deltoid; LLD: left lateral deltoid; LPD: left posterior deltoid; RBB: right biceps brachii; RAD: right anterior deltoid; RLD: right lateral deltoid; RPD: right posterior deltoid.

*denotes correlation coefficient significantly different from zero, t test.

operations through the reports of the 3D gait analysis. It is not surprising that RATAF is accompanied by augmented motor outputs in both mean and max sEMG activity, which is the same as our expectation and has also been reported in Hof et al.³¹

Influences of controller and robot on sEMG activity

It can be seen from Figures 3 and 4 that the training protocols with (RATC) and without (RAT) the

controller do not have significant differences in the sEMG activity for all the muscles. It means the controller does not affect the activity level of each muscle and can keep stable for the exercises without being affected by internal and external disturbances (Figure 5(a)). This is the foundation for bilateral training. As for the influence of the robots, significant differences are found between RAT (RATC) and NT. It is believed that the changes in muscle activity can be explained primarily due to the weight of the arms, which is supported by

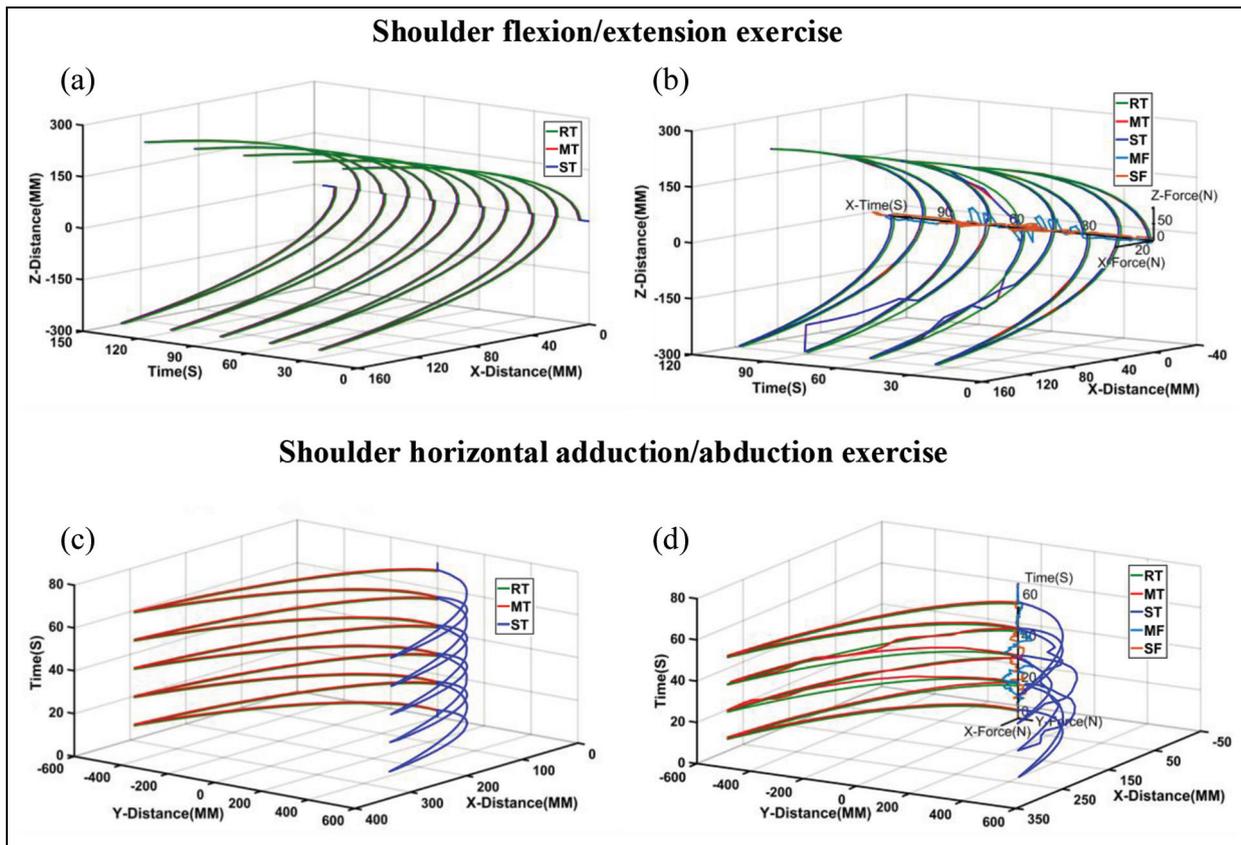


Figure 5. Trajectories and interaction force: (a) trajectories of shoulder flexion/extension exercise with the controller (RATC), (b) trajectories of shoulder flexion/extension exercise with active force (RATAF), (c) trajectories of shoulder horizontal adduction/abduction exercise with the controller (RATC) and (d) trajectories of shoulder horizontal adduction/abduction exercise with active force (RATAF; RT, MT, ST, MF and SF in these figures mean reference trajectory, master trajectory, slave trajectory, master force and slave force, respectively).

the results of,^{28,29} and has been described above. However, even in the active force-involved robot-assisted training (RATAF), there are not many significant differences between RATAF and NT, especially in the mean sEMG activity (Figure 3(a) and (b)). The main reason could be the same as RAT (RATC) that the muscles do not need to make an effort to counteract gravity.²⁸ The second reason could be the inertia of the arms, which is in agreement with the result of Hidler and Wall.¹³ In other words, the slower movement can result in a lower variability in the EMG patterns, and reduce the level of muscle activity. In our work, the movement in RATAF is slower than that in NT (24°s for RATAF and 4°s for NT). The reason for choosing the slow movement is that 10°/s is a reasonable speed for most stroke patients to follow, without being too difficult to achieve, or too easy to lost interest in quickly based on the finding in Hu et al.²⁵ Furthermore, according to Guo et al.³² and Grasso et al.,³³ the muscle activity patterns can be affected by moving postures, and according to Hidler and Wall,¹³ the restriction of movements could increase the level of muscle activity due to some antagonistic muscles. During our experiment, the moving postures of the participants cannot be controlled very precisely, since the

proposed rehabilitation system is based on an “end-effector” robot. This kind of robot has been widely used in rehabilitation research (such as the MIME), even though it mainly focuses on end-point movements rather than joint-specific movements.

Muscle activation correlations during bilateral training

One purpose of this work is to explore the activation correlations of different muscles during bilateral training. The major finding is that any specific muscle has the strongest correlation to the same muscle of the contralateral arm in all different training protocols (with and without robots’ assistance) and in both exercises (Tables 3 and 4). This finding can be supported and explained by Shumway-Cook and Woollacott.³⁴ The brain and the corresponding motor nerve system prefer to use the same muscle of each arm to do the same movement for counterbalancing weight of the whole body. In addition, based on previous work,³⁵ this finding has been used in robot control strategies for decades (especially for force control). The second finding is brand new that activation correlations are related to

Table 5. Trajectory error (mm) of RATC and RATAF.

Exercise name	Protocol name	Max error	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Mean \pm SD
Flexion/ extension	RATC	x axis	2.22	2.22	2.48	2.62	2.22	2.22	1.98	2.12	2.38	2.32	2.05 \pm 0.17
		z axis	0.37	0.37	0.37	0.27	0.27	0.37	0.27	0.37	0.43	0.37	0.35 \pm 0.05
	RATAF	x axis	9.38	3.48	7.22	4.72	3.68	3.42	8.68	2.78	6.88	2.58	5.28 \pm 2.40
		z axis	2.57	3.47	6.97	2.47	0.27	4.67	1.23	0.37	9.77	0.33	3.21 \pm 2.99
Adduction/ abduction	RATC	x axis	2.42	2.42	2.68	2.89	2.42	2.42	2.98	3.12	2.69	2.75	2.68 \pm 0.25
		y axis	1.37	1.37	1.37	2.27	1.27	1.37	2.27	1.37	1.43	1.37	1.55 \pm 0.36
	RATAF	x axis	8.69	5.69	3.88	1.59	9.58	6.33	7.49	6.38	2.58	3.11	5.53 \pm 2.54
		y axis	1.58	5.21	6.18	1.44	2.36	6.21	1.47	2.58	3.32	2.23	3.26 \pm 1.81

All results are absolute values. RATC: robot-assisted trajectory training with the controller; RATAF: robot-assisted trajectory training with active force.

the active force exhibited by muscles in bilateral training; that is, the bigger force created the stronger correlation coefficient. This is also why RATAF presents the strongest correlations among four training protocols. The third finding is that ADs and LDs show the strongest correlation coefficients in all the training protocols compared to other muscles in the flexion/extension and the adduction/abduction exercises, respectively. One reason could be that a pair of muscles showing the largest sEMG activity can also present the strongest correlation to each other. The same conclusion has been reported in Staudenmann et al.³⁶ in which participants are asked to perform the isometric contraction at 20% of MVC torque until failure. However, one exception is found in the adduction/abduction exercise that LPD muscle does not show the strongest correlation with RPD muscle in RAT and RATC. One possible reason is the individual differences among participants, which is the same finding of Sylos-Labini et al.¹¹ It can be seen from Table 4, in RAT, that the correlation coefficient of PDs is 0.88 ± 0.12 , which is very close to the strongest correlation coefficient of LPD muscle (LPD to RLD muscle, 0.90 ± 0.04). Meanwhile, the SD value of the expected muscle (RPD) is much bigger than the actual muscle (RLD; 0.12 vs. 0.04).

Robot-assisted bilateral training and clinical significance

As previously mentioned, the controller can adjust trajectories according to the force applied by participants and thus to measure their voluntary efforts, which is the second purpose of RATAF. The experimental results of RATC and RATAF are shown in Figure 5 and Table 5. It can be seen from Figure 5(a) and (c) that the master and slave robots follow the RT very well, while in Figure 5(b) and (d), the trajectories of the master and slave robots can either be different from the RT in second and third rounds according to the active force, or be the same as the RT in fourth round when the active force descends to the safety threshold (15 N). From these results, it can be observed that the proposed robot-assisted training is stable, and participants' voluntary efforts can be represented by the adjusted

trajectories. Even though the current findings imply that muscle activation patterns in the robot-assisted training are significantly different than those in the robot-unassisted training, the clinical applications of these kinds of bilateral training are not necessarily negative based on the findings of literature.^{11–13} During the primary recovery stages (RAT and RATC), the affected arms of participants can be moved carefully by the slave robot with consistent and time-unlimited training sessions. These types of training are found to be effective in reducing hypertonia and maintaining joint stability, which was concluded in Schmit et al.³⁷ After recovering a certain degree of muscle strength, the robot-assisted cooperative training would be used (RATAF), in which participants can adjust trajectories through their active force. As discussed in the introduction section and according to the finding of Rossini and Dal Forno,⁵ voluntary effort-involved motion is more effective for motor functional improvement. Therefore, the proposed robot-assisted bilateral training has the potential to be used in clinical trials as a new training method. Meanwhile, with the help of sEMG signals, the participation levels of participants can be analyzed precisely, which can be treated as an index to investigate whether the robot-assisted bilateral training can stimulate the active participation of stroke patients and subsequently maximize therapeutic outcomes.

Limitation and future work

As a pilot study, only healthy male participants were recruited for this experiment, which means that the findings and the explanations cannot necessarily be extrapolated to female participants or other age groups as well as stroke patients, and the effectiveness of the proposed training protocols cannot be validated. Meanwhile, some negative feedback was also collected after the exercises, such as no visual guidelines, no virtual reality games, and the wires of EMG electrodes will influence movements at some extreme points for very tall participants (≥ 190 cm). To reduce these side effects, verbal guidelines were used, and none of the participants were taller than 190 cm (Table 1). Meanwhile, as shown in Table 5, the max errors in the

flexion/extension exercise and the adduction/abduction exercise were 9.77 mm and 9.58 mm, which could be regarded as less than minor compared to the maximum distances of 350 mm (z axis) and 500 mm (x axis; percentage error: 2.79% and 1.92%), respectively. Therefore, the experimental results were still valid and reliable. Future work will be done in three aspects as a result of the limitations and feedback, to improve the system's performance, collect more accurate results and evaluate the effectiveness of bilateral training: (1) more healthy participants will be involved to find out the influence of gender and age (e.g. the elderly (aged 65 years and older)); (2) stroke patients will be recruited to explore the difference of muscle activation patterns, and to evaluate the validity of the proposed training protocols and (3) wireless EMG equipment will be utilized to provide a more comfortable training environment, thus measuring more precise sEMG signals in real time.

Conclusion

Overall, the experimental result is the same as our hypothesis that there are significant differences between the robot-assisted training and the robot-unassisted training, which can be supported by reliable sources.^{11,13,28,29} Specifically, for healthy participants, the activity of the upper arm muscles would be reduced in the robot-assisted training while increased in the active force-involved robot-assisted training compared to the robot-unassisted training in both exercises.^{11,13} The results also show that the controller does not affect the muscle activation patterns during any training protocols, and the voluntary effort of the participants can be represented through the adjusted trajectories. Furthermore, an activation correlation between different muscles under different exercises is represented by the results as well; that is, any specific muscle has the strongest correlation to the same muscle of the contralateral arm, both with and without robots' assistance, which can be confirmed via prior research.^{34,35} The other finding is that the activation correlations are positively related to the active force in different bilateral training protocols, which is a brand-new finding concluded by our experiment. These findings can assist in the understanding of bilateral recovery processes during different training protocols and different exercises as well as human-robot interactions. In addition, the results and the corresponding explanations could possibly be the primary baseline of bilateral exercises to assess the results of later experiments carried out by stroke patients.

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