Short-term Tai Chi Training May Benefit Arterial Compliance But Not Heart Rate Variability Among Stroke Survivors: A Randomized Controlled Trial

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Abstract

Background

Arterial stiffening and cardiac autonomic dysregulation are common among stroke survivors. These changes increase the risk of cardiovascular problems and tend to accelerate mortality. Tai Chi has been reported to improve arterial compliance and cardiac autonomic regulation among healthy older adults. Such effects have not been examined among stroke survivors.

Objectives

This study aimed at investigating the effect of Tai Chi training on arterial stiffness and the functioning of the cardiac autonomic nervous system among stroke survivors.

Methods

This was an assessor-blinded randomized controlled trial. Fifty-six community-dwelling stroke survivors were randomized into three groups; a group which received Tai Chi training (n = 19), another which received conventional exercise training (n = 18), or control groups (n = 19). The subjects in the former two groups were trained for an hour twice a week for 12 weeks. No training was provided to the control group. Outcome measures were large and small arterial compliance, blood pressure, and heart rate variability (normalized low and high frequency power and the low frequency to high frequency ratio). Assessments were conducted before and after the intervention period. Two-way mixed analysis of variance was employed to compare the three intervention groups and the two assessment time points.

Results

On average, small arterial compliance increased about 13.5% after Tai Chi training and about 9.5% after the conventional exercise training. It decreased among the controls (-10.6%). A significant improvement in average systolic blood pressure was also observed after the Tai Chi training, while no significant change was found in the other two groups. No significant change was observed in the heart rate variability parameters.

Conclusions

Tai Chi training may benefit stroke survivors by decreasing small artery stiffness and reducing systolic blood pressure. However, the short term Tai Chi training did not improve cardiac autonomic regulation in this population.

Keywords

Tai Chi; stroke; arterial compliance; blood pressure; cardiac autonomic regulation; heart rate variability; randomized controlled trial

Trial Registration

The study was retrospectively registered in ClinicalTrial.gov on 16 August 2017 (registration number: NCT03252236)

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Background

Prior studies have shown that increased arterial stiffness [1, 2] and dysfunction of the cardiac autonomic nervous system[3] are relatively common among stroke survivors. Such changes raise the risk of cardiovascular problems and tend to accelerate mortality.[4–6] Aerobic exercise has been suggested to reduce arterial stiffness [7–9] and improve the cardiac autonomic modulation[10] of healthy subjects.

Tai Chi is a Chinese traditional martial art which has been employed as a rehabilitation exercise in recent decades. Previous studies have reported its effect on arterial compliance[11] and cardiac autonomic regulation [12, 13] among older adults. Tai Chi is considered a mind-body exercise of moderate intensity with aerobic features.[14] When practicing Tai Chi, practitioners maintain a relaxed status of mind and breathe slowly but deeply. These features have been found to benefit the regulation of sympathetic and parasympathetic activities [15–17], and may also reduce arterial stiffness[10] among healthy older adults.

Tai Chi benefits arterial stiffness and cardiac autonomic regulation among healthy older adults, suggesting that the exercise may also benefit stroke survivors. This randomized and controlled trial was therefore designed to explore the effect of Tai Chi training on arterial stiffness and functioning of the cardiac autonomic nervous system among stroke survivors. The hypothesis was that subjects being trained in Tai Chi would show reduced arterial stiffness and improved autonomic modulation of the heart. Owing to the unique features of this mind-body exercise, Tai Chi was expected to be more beneficial than conventional exercises.

Methods

Participants

The study was retrospectively registered in ClinicalTrials.gov on 16 August 2017 (Registration number: NCT03252236). The study was conducted from October 2014 to December 2016. Community-dwelling stroke survivors were recruited through patient self-help groups and hospitals in Hong Kong. The subjects were included if they were aged at least 50, had suffered a stroke at least six months previously, were able to walk unaided for 5 meters indoors, and were able to follow verbal instructions. Those suffered from any neurological disease other than stroke, had received any cardiac surgery, had received any major surgery during the previous six months or who scored less than 18 on the Cantonese version of the Mini-Mental State Examination[18] were excluded. This study was approved by the Ethics Committee of the Hong Kong Polytechnic University (Reference number: HSEARS20131023003). A written informed consent form was obtained from every subject after the aims and procedures of the study had been fully explained. The intervention was conducted at the Hong Kong Polytechnic University and in community centers. The assessment was carried out at the university.

There were three intervention groups: Tai Chi group, conventional exercise group, and control group. Eligible subjects were first stratified according to their gender and age (aged 50–59, 60–69, 70–79, or ≥80 years old) and then randomized into one of the three intervention groups by drawing lots.

Interventions

The subjects in the Tai Chi and conventional exercise groups were trained in hour-long sessions twice a week for 12 weeks. They were also asked to practice outside of the class for at least 30 minutes once a week. Exercise log-books were given to the subjects in which they were instructed to record the amount of self-training. The class began with a 10-minute warm-up, followed by 45 minutes of the corresponding exercises and a 5-minute cooling down period.

According to the ability and needs of the stroke survivors in the Tai Chi group, traditional Yang-style Tai Chi was modified into 12 forms by a senior physiotherapist and a Tai Chi master with more than 30 years of experience in teaching Tai Chi. The training was instructed by a physiotherapist who is also a Tai Chi practitioner. The class size was limited to 10 participants in order to provide adequate supervision and safety for each subject. Physical support and standby assistance by the instructor were provided if necessary. The support was gradually withdrawn once the subjects were able to maintain balance on their own. Resting periods were allowed whenever needed. During the training, the subjects were encouraged to breathe slowly and concentrate and be relaxed.

The subjects in the conventional exercise group performed conventional exercises included mobilization, stretching, muscle strengthening and walking. The class was instructed by the same physiotherapist who

conducted the Tai Chi classes. No specific instructions were given on the breathing pattern, concentration, and relaxation.

The subjects in the control group were not encouraged to do any special exercises during the study period, but they were allowed to continue any physical activities they had been practicing before enrolling in the study. After the completion of all the assessments, the subjects in the conventional exercise group and the control group were given the Tai Chi training.

Assessments

Demographic data and information related to each subject's stroke were collected as baseline data. The presence of any comorbidity which might affect arterial compliance and cardiac autonomic regulation including hypertension, cardiovascular diseases, diabetes mellitus, and dyslipidemia were recorded.[19] Any changes in these conditions and the medication the subjects were taking were tracked during the study period along with the regular exercise habits of all the subjects.

Assessments were conducted before the experiment and after the entire intervention period. The measurements were carried out between 9 am and 1 pm in a controlled environment kept at 22 ± 1 °C. The subjects were instructed to refrain from consuming beverages containing alcohol or caffeine and to avoid aerobic exercise during the day before the measurements. The Subjects rested in a supine posture for at least 10 minutes before being assessed.[3, 20, 21]

Arterial stiffness was measured with a non-invasive CR-2000 cardiovascular profiling system (Hypertension Diagnostics, Inc., Eagan, Minnesota). Brachial blood pressure was measured with a conventional blood pressure cuff positioned around the subject's upper arm on the affected side while lying supine. An arterial tonometer sensor was placed over the wrist of the less-affected arm where the radial pulsation was the maximum to record the waveforms in the artery for 30 seconds. The wrist was stabilized to minimize any movement during the measurements. The diastolic decay of the waveforms was analyzed to calculate the compliance of the large and small arteries by applying a modified Windkessel model.[22–24] The measurements were conducted three times, and the averages of the large and small arterial compliance and the brachial systolic and diastolic blood pressure were treated as outcome measures. This method of measuring arterial compliance has been validated and shown to have good repeatability.[25, 26]

Autonomic regulation of every subject's heart was evaluated in terms of heart rate variability. The RR interval was recorded for five minutes with the subject supine using a Model RS800 heart rate monitoring instrument (Polar Electro Ltd., Kempele, Finland). That device has been shown to be validated and reliable.[27] The variability in the RR interval was transformed into the frequency domain of heart rate variability using a fast Fourier transform spectral analysis algorithm (Ver 13.2.2, Nevrokard, Slovenia). Low frequency (0.04–0.15 Hz) and high frequency (0.15–0.40 Hz) power spectral densities were generated. The low and high frequency power were normalized using the total power, and together with the low frequency to high frequency ratio were employed as the outcome measures. The high frequency power of heart rate variability has been suggested to represent parasympathetic activity, while the low frequency power reflects both sympathetic and parasympathetic activities. The low frequency to high frequency ratio has been regarded as an indicator of the balance between the sympathetic and parasympathetic activities.[28]

Statistical analysis

Baseline comparisons among the three groups were conducted using one-way analysis of variance (ANOVA) for the continuous data and chi-squared values for the categorical data. Two-way mixed ANOVA (group x time) was employed to compare the three intervention groups and the two assessment time points. Post-hoc analysis was adjusted for the least significant difference. The significance level was set at 0.05. Missing data were handled by carrying forward the last observation according to the intention-to-treat method. Subjects who changed their medications for treating hypertension, diabetes mellitus, dyslipidemia, cardiac disease or any blood-related problems were treated as having dropped out from the study. Any parameter found significantly different among the three groups in the baseline measurement was treated as a covariate in the two-way mixed ANOVA.

Results

Figure 1 shows the CONSORT diagram describing the study. 88 subjects were enrolled initially. After screening for their eligibility, 56 subjects were randomized into three groups: the Tai Chi group (n=19), the conventional exercise group (n=18), or the control group (n=19).

There was a significant difference in the number of subjects who suffered from diabetes mellitus among the three groups so that the factor is treated as a covariate. Table 1 presents demographic data describing the subjects.

No adverse effects related to the assessment or the interventions were reported.

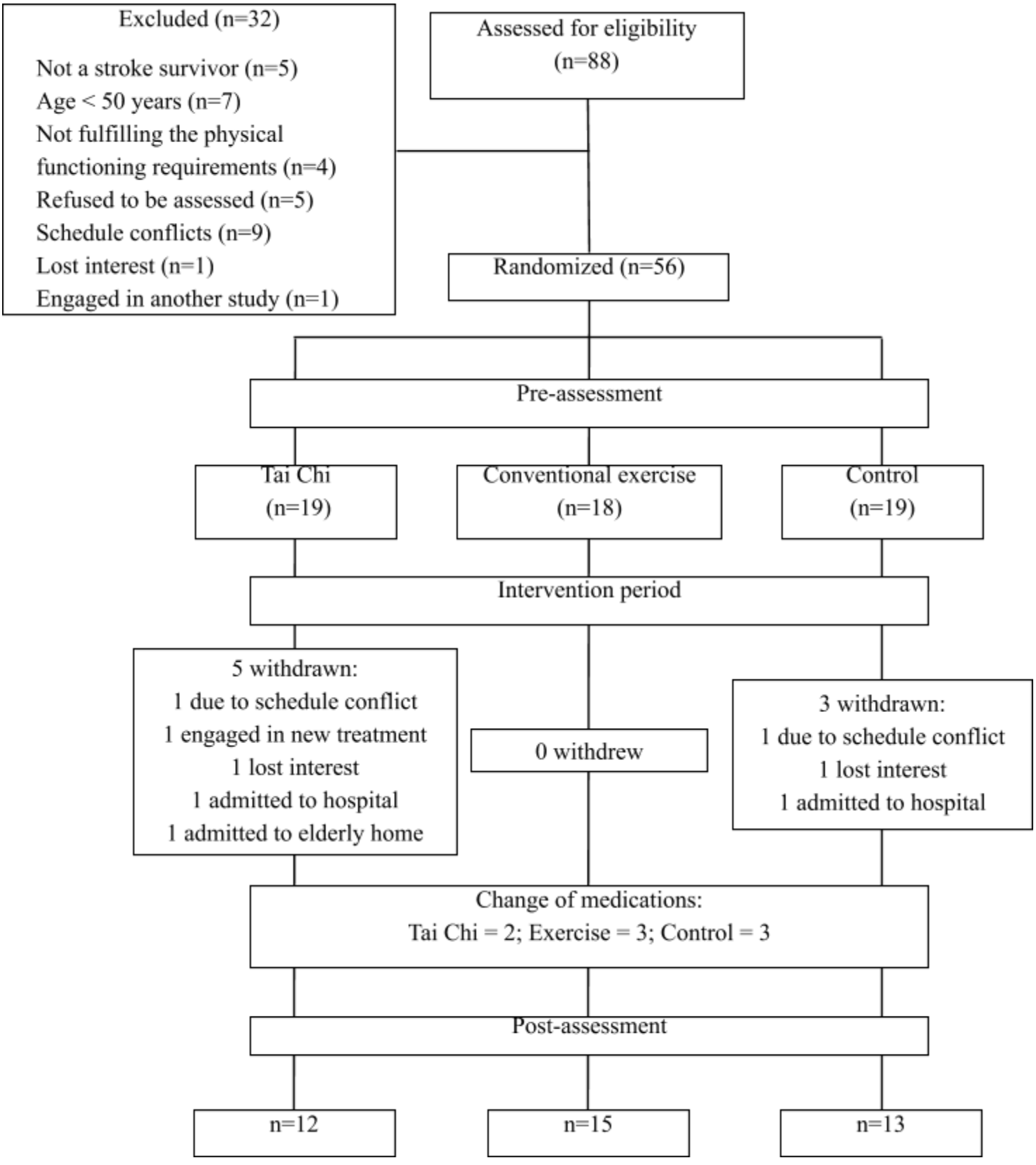
Table 1. Demographic and clinical characteristics of the subjects.

		Tai Chi (n=19)	Exercise (n=18)	Controls (n=19)	*p*-value
Gender (Male : Female)		10 : 9	10 : 8	8 : 11	0.688
Age (years)		64.2 ± 8.2	62.2 ± 7.4	61.8 ± 7.3	0.584
Height (cm)		161.4 ± 7.0	163.3 ± 9.5	160.3 ± 7.0	0.516
Weight (kg)		60.9 ± 8.1	64.1 ± 10.1	657.4 ± 11.2	0.132
Comorbidities (number)					
Hypertension		14	11	11	0.500
Diabetes mellitus		7	7	1	0.024[a]
Dyslipidemia		9	9	10	0.981
Cardiac disease		3	7	1	0.138
Chronicity (years)		5.6 ± 6.4	9.5 ± 11.9	5.3 ± 4.1	0.226
Affected side	Right	9	7	8	0.870
	Left	10	11	11	
Type of stroke	Ischemic	14	10	12	0.377
	Haemorrhage	3	6	7	
	Both	2	2	0	
Number of strokes	1	14	14	16	0.631
	2	4	2	2	
	3	0	1	1	
	>3	1	1	0	
Attendance (out of 24 sessions)		21.3 ± 3.6	19.3 ± 3.8	/	0.124

Note: values are means ± standard deviation

[a] denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group

Figure 1. CONSORT diagram summarizing the randomized and controlled trial**.**



Arterial compliance and blood pressure

Table 2 presents the blood pressure and arterial compliance results. The average small arterial compliance was significantly lower in the Tai Chi group than in either of the other groups at baseline. Those data were therefore treated as a covariate in the statistical analysis.

A significant interaction effect was found in the small arterial compliance data [F (2,49) = 4.26, p = 0.02]. A follow-up analysis revealed that the control group differed from the Tai Chi group (p = 0.01) and the conventional exercise group (p = 0.02) in the post-assessment when the baseline values and the number of diabetic subjects in each group were treated as covariates. Both the Tai Chi group and the conventional exercise group showed increases in the average small arterial compliance (of 13.5% and 9.5%, respectively), while a reduction was observed in the controls (-10.6%). Moreover, the change in small arterial compliance was significant in the Tai Chi group (p = 0.05). No significant between-subject or within-subject differences in large arterial compliance were observed.

Significant within-subject changes in systolic blood pressure [F (1,49) = 3.14, p = 0.05] were observed. A follow-up analysis showed a reduction in average systolic blood pressure in the Tai Chi group after the intervention (p = 0.004). No significant change was detected in the conventional exercise or control group averages. In the post-assessment, however, there was no significant difference among the three groups. There was a significant group difference in diastolic blood pressure [F (2,49) = 4.149, p = 0.02]. Further analysis revealed a significantly lower value in the conventional exercise group than the control group (p = 0.003).

Table 2. Changes in arterial compliance and blood pressure

				***F*-value (*p*-value)**		
	Group	**Pre**	**Post**	**Between-subject effect**	**Within-subject effect**	**Interaction effect**
Large arterial compliance (ml/mmHg*10)	TC	10.8 ± 4.3	10.9 ± 4.3	1.05 (0.35)	1.15 (0.29)	1.30 (0.28)
	EX	12.5 ± 3.6	13.4 ± 4.4			
	CON	12.0 ± 2.8	11.5 ± 3.0			
Small arterial compliance (ml/mmHg*100)	TC	3.7 ± 2.0[a,c]	4.2 ± 2.2[b,c]	0.61 (0.44)	1.34 (0.25)	4.26 (0.02)*
	EX	4.2 ± 2.0[a]	4.6 ± 2.4[b]			
	CON	4.7 ± 2.0[a]	4.2 ± 2.1[b]			
SBP (mmHg)	TC	129.2 ± 17.3[c]	125.0 ± 18.6[c]	0.94 (0.40)	0.62 (0.44)	3.14 (0.05)*
	EX	120.5 ± 10.5	118.5 ± 8.1			
	CON	120.1 ± 13.5	120.1 ± 15.8			
DBP(mmHg)	TC	70.8 ± 7.6	70.3 ± 7.6	4.15 (0.02)*	2.34 (0.13)	1.30 (0.08)
	EX	66.9 ± 5.9	65.8 ± 5.8[d]			
	CON	70.8 ± 7.3	71.7 ± 8.1[d]			

Note: values are means ± standard deviation

Pre = pre-assessment; Post = post-assessment; SBP = systolic blood pressure; DBP = diastolic blood pressure; TC = Tai Chi group; EX = conventional exercise group; CON = control group

* denotes a significant effect in two-way mixed ANOVA ($p \leq 0.05$)

[a] denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group in the pre-assessment ($p \leq 0.05$)

[b] denotes a significant difference between the Tai Chi group and the control group or between the conventional exercise group and the control group in the post-assessment ($p \leq 0.05$)

[c] denotes a significant difference between the pre- and post-assessment values ($p \leq 0.05$)

[d] denotes a significant difference between the conventional exercise group and the control group in the post-assessment ($p \leq 0.05$)

Heart rate variability

Table 3 presents the heart rate variability data. No significant changes were observed either within a group or among the three groups.

Table 3. Changes in heart rate variability

				F-value (*p*-value)		
	Group	**Pre**	**Post**	**Between-subject effect**	**Within-subject effect**	**Interaction effect**
nLF (nu)	TC	47.9 ± 24.8	45.7 ± 18.4	0.25	0.13	0.11
	EX	42.6 ± 16.8	44.7 ± 18.6	(0.78)	(0.72)	(0.90)
	CON	42.3 ± 19.4	45.4 ± 17.6			
nHF (nu)	TC	40.5 ± 22.4	43.0 ± 16.5	0.34	0.28	0.14
	EX	45.8 ± 17.4	45.2 ± 19.3	(0.72)	(0.60)	(0.87)
	CON	48.5 ± 17.6	45.9 ± 16.8			
LF/HF	TC	2.2 ± 2.3	1.6 ± 1.5	0.42	0.16	1.12
	EX	1.3 ± 1.2	1.6 ± 2.2	(0.66)	(0.70)	(0.34)
	CON	1.3 ± 1.4	1.4 ± 1.6			

Note: values are means ± standard deviation
Pre = pre-assessment; Post = post-assessment; nLF = normalized low frequency; nHF = normalized high frequency; LF/HF = the ratio of low frequency to high frequency; TC = Tai Chi group; EX= conventional exercise group; CON = control group

Discussion

After adjusting for the baseline differences, the subjects in the Tai Chi and conventional exercise groups showed significantly greater small arterial compliance than the controls after the interventions. Indeed, the data demonstrated enhanced small arterial compliance in the Tai Chi and conventional exercise groups, but a decline in the control group. The subjects in the Tai Chi group also showed a significant reduction in average systolic blood pressure after the training. However, no significant changes were observed in their average large arterial compliance, diastolic blood pressure or heart rate variability after the 12 weeks of training.

The difference in average arterial stiffness among the three groups observed in the post-assessment may imply a beneficial effect of Tai Chi and conventional exercise in terms of delaying the deterioration of small arterial compliance among stroke survivors. These results agree with those of prior studies focusing on elderly women[11] and women with rheumatoid arthritis.[29] Small arterial compliance has been suggested as an independent predictor of cardiovascular events.[30] Improving it may also protect organs such as brain, which have low vascular resistance to stress, from large pressure force.[31] Slowing the process of small artery stiffening through Tai Chi or other training may therefore reduce the risk of cardiovascular disease and the recurrence of stroke among stroke survivors. The lack of any significant difference between the Tai Chi group and the conventional exercise group implies that the two types of training have similar effects on small arterial compliance.

The aerobic nature of the exercises may explain the observed changes in small arterial compliance. Moderate intensity exercises like Tai Chi[14] have been shown to decrease arterial stiffness.[7–9] The exact mechanism of that effect is still not completely understood, but it is generally accepted that improved endothelial function and increased bioavailability of nitric oxide in the arterial system may be involved.[8, 32] Indeed, prior studies have documented better endothelial function in older,

experienced Tai Chi practitioners[33] and in women with rheumatoid arthritis after three months of Tai Chi training.[29] Another study has shown that 12 weeks of Tai Chi training can upregulate nitric oxide in the blood among patients with untreated hypertension.[34] These studies may provide some insight into how Tai Chi training would enhance arterial compliance. Nevertheless, further studies have to be conducted to elucidate the exact mechanisms involved.

In contrast to small arterial compliance, no significant difference in large arterial compliance was observed in comparing the three groups. Previous studies have suggested that the effect of aging in terms of structural changes in the arterial system is more prominent in the large than in the small arteries. The large arteries may therefore take longer to show any significant change in response to exercise training.[21, 23] Whether a longer period of Tai Chi training would benefit large arterial compliance is needed to be further investigated.

A recent meta-analysis has suggested that Tai Chi training can lower blood pressure among healthy older adults.[35] The results of this study probably extend that finding to stroke survivors. However, it should be pointed out that no significant difference was found among the three groups in the post-assessment. So, the hypothesis that Tai Chi is better than the conventional exercise in terms of blood pressure control was not supported in this study.

The hypothesized improved cardiac autonomic regulation also was not supported by the data. Previous clinical trials have demonstrated a significant decrease in the low frequency power and a significant increase in the high frequency power of heart rate variability after Tai Chi training.[12, 13] That would imply a reduction in sympathetic activity and enhanced parasympathetic activity. The mechanisms proposed for such effects refer to the slow and deep breathing [15, 16] and concentration and relaxation[17] involved during Tai Chi practice. All of the subjects in this study displayed some degree of physical disability. It is possible that they needed more attention to maintain balance and longer practice to acquire good Tai Chi technique. Thus, they may not have been able to focus sufficiently on concentration, relaxation and slow, deep breathing during the practice. Indeed, prior studies of older people with no physical impairment have found that it took a total of 36 hours of Tai Chi training to generate a significant improvement in heart rate variability.[12, 13] The length of previous studies is 12 hours more than that of this study. Future investigation employing a longer training period and better emphasizing concentration, relaxation, and slow, deep breathing is needed if autonomic regulation is the main concern. Moreover, longer post-intervention measurement time may have uncovered a difference and could be considered for future studies.

In interpreting these results, it is important to recall that the subjects were self-recruited. They probably represent a more active group within the population. In addition, the requirements that they be able to walk five meters unaided indoor may have eliminated many more feeble yet otherwise typical stroke survivors. These selection biases tend to limit the generalizability of the study's results only to relatively able stroke survivors. Another limitation is the small sample size. Further studies with a larger sample are needed because with this small sample, sub-group analysis of the differences in small arterial compliance based on the side and location of the stroke were not possible.[36] A limitation related to the assessment is that the breathing rate was not controlled. It is known to affect heart rate variability.[16] However, slow and deep breathing is an intrinsic characteristic of Tai Chi, so controlling the breathing rate during the assessment may have biased the heart rate variability results.

Conclusions

The data suggest a beneficial effect of Tai Chi training in terms of delaying the decline in small arterial compliance and reducing systolic blood pressure among stroke survivors. These effects were not, however, significantly better than those achievable through conventional exercise. The data were insufficient to support the expectation that short-term Tai Chi training would improve cardiac autonomic regulation in this population. Studies with a larger sample and employing a longer term of Tai Chi training are warranted. The mechanisms of the effects of Tai Chi on arterial compliance and cardiac autonomic regulation are also suggested for further exploration.

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Appendix

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Abbreviations
ANOVA: analysis of variance; CON: control group; DBP: diastolic blood pressure; EX: conventional exercise group; LF/HF: the ratio of low frequency to high frequency of heart rate variability; nHF: normalized high frequency of heart rate variability; nLF: normalized low frequency of heart rate variability; Post: post-assessment; Pre: pre-assessment; SBP: systolic blood pressure; TC: Tai Chi group

Ethics approval and consent to participate
This study was approved by the Ethics Committee of the Hong Kong Polytechnic University (Reference number: HSEARS20131023003). A written informed consent form was obtained from every subject after the aims and procedures of the study had been fully explained.

Consent for publication
Not applicable.

Availability of data and materials
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interest.

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References

1. Sugioka K, Hozumi T, Sciacca RR, Miyake Y, Titova I, Gaspard G, Sacco RL, Homma S, Di Tullio MR. Impact of aortic stiffness on ischemic stroke in elderly patients. Stroke. 2002;33:2077–2081. doi:10.1161/01.STR.0000021410.83049.32.
2. Tuttolomondo A, Di Sciacca R, Di Raimondo D, Serio A, D'Aguanno G, Pinto A, Licata G. Arterial stiffness indexes in acute ischemic stroke: Relationship with stroke subtype. Atherosclerosis. 2011;211:187–194. doi:10.1016/j.atherosclerosis.2010.02.010.
3. Xiong L, Leung HH, Chen XY, Han JH, Leung TW, Soo YO, Chan AY, Lau AY, Wong LK. Comprehensive assessment for autonomic dysfunction in different phases after ischemic stroke. Int J Stroke. 2013;8:645–651. doi:10.1111/j.1747-4949.2012.00829.x.
4. Mäkikallio M, Mäkikallio TH, Korpelainen JT, Sotaniemi KA, Huikuri HV, Myllylä VV. Heart rate dynamics predict poststroke mortality. Neurology. 2004;62:1822–1826. doi:10.1212/01.WNL.0000125190.10967.D5.
5. Tsivgoulis G, Vemmos K, Papamichael C, Spengos K, Manios E, Stamatelopoulos K, Vassilopoulos D, Zakopoulos N. Common carotid artery intima-media thickness and the risk of stroke recurrence. Stroke. 2006;37:1913–1916. doi:10.1161/01.STR.0000226399.13528.0a.
6. Calvet D, Touzé E, Laurent S, Varenne O, Sablayrolles JL, Boutouyrie P, Mas JL. Aortic stiffness measurement improves the prediction of asymptomatic coronary artery disease in stroke/transient ischemic attack patients. Int J Stroke. 2014;9:291–296. doi:10.1111/ijs.12015.
7. Tanaka H, Dinenno FA, Monahan KD, Clevenger CM, DeSouza CA, Seals DR. Aging, habitual exercise, and dynamic arterial compliance. Circulation. 2000;102:1270–1275. doi:10.161/01.CIR.102.1270.
8. Seals DR, Desouza CA, Donato AJ, Tanaka H. Habitual exercise and arterial aging. J Appl Physiol. 2008;105:1323–1332. doi:10.1152/japplphysiol.90553.2008.
9. Fujimoto N, Prasad A, Hastings JL, Arbab-Zadeh A, Bhella PS, Shibata S, Palmer D, Levine BD. Cardiovascular effects of 1 year of progressive and vigorous exercise training in previously sedentary individuals older than 65 years of age. Circulation. 2010;122:1797–1805. doi:10.1161/CIRCULATIONAHA.110.973784.
10. Micieli G, Cavallini A. The autonomic nervous system and ischemic stroke: A reciprocal interdependence. Clin Auton Res. 2008;18:308–317. doi:10.1007/s10286-008-0495-7.
11. Lu X, Hui-Chan CW, Tsang WW. Effects of Tai Chi training on arterial compliance and muscle strength in female seniors: A randomized clinical trial. Eur J Prev Cardiol. 2013;20:238–245. doi:10.1177/2047487311434233.
12. Audette JF, Jin YS, Newcomer R, Stein L, Duncan G, Frontera WR. Tai Chi versus brisk walking in elderly women. Age Ageing. 2006;35:388–393. doi:10.1093/ageing/afl006.
13. Chang RY, Koo M, Yu ZR, Kan CB, Chu IT, Hsu CT, Chen CY. The effect of t'ai chi exercise on autonomic nervous function of patients with coronary artery disease. J Altern Complement Med. 2008;14:1107–1113. doi:10.1089/acm.2008.0166.
14. Lan C, Lai JS, Wong MK, Yu ML. Cardiorespiratory function, flexibility, and body composition among geriatric Tai Chi Chuan practitioners. Arch Phys Med Rehabil. 1996;77:612–616. doi:10.1016/S0003-9993(96)90305-6.
15. Figueroa MA, DeMeersman RE, Manning J. The autonomic and rate pressure product responses of Tai Chi practitioners. N Am J Med Sci. 2012;4:270–275. doi:10.4103/1947-2714.97208.
16. Lu WA, Kuo CD. Breathing frequency-independent effect of Tai Chi Chuan on autonomic modulation. Clin Auton Res. 2014;24:47–52. doi:10.1007/s10286-014-0224-3.
17. Fong SS, Wong JY, Chung LM, Yam TT, Chung JW, Lee YM, Chow LP, Luk WS, Ng SS. Changes in heart-rate variability of survivors of nasopharyngeal cancer during Tai Chi Qigong practice. J Phys Ther Sci. 2015;27:1577–1579. doi:10.1589/jpts.27.1577.
18. Lam LC, Tam CW, Lui VW, Chan WC, Chan SS, Wong S, Wong A, Tham MK, Ho KS, Chan

WM, Chiu HF. Prevalence of very mild and mild dementia in community-dwelling older Chinese people in Hong Kong. Int Psychogeriatr. 2008;20:135–148. doi:10.1017/S1041610207006199.
19. Cavalcante JL, Lima JA, Redheuil A, Al-Mallah MH. Aortic stiffness: Current understanding and future directions. J Am Coll Cardiol. 2011;57:1511–1522. doi: 10.1016/j.jacc.2010.12.017.
20. Laurent S, Cockcroft J, Van Bortel L, Boutouyrie P, Giannattasio C, Hayoz D, Pannier B, Vlachopoulos C, Wilkinson I, Struijker-Boudier H. Expert consensus document on arterial stiffness: Methodological issues and clinical applications. Eur Heart J. 2006;27:2588–2605. doi: 10.1093/eurheartj/ehl254.
21. Nickel KJ, Acree LS, Gardner AW. Effects of a single bout of exercise on arterial compliance in older adults. Angiology. 2011;62:33–37. doi: 10.1177/0003319710381993.
22. Cohn JN, Finkelstein S, McVeigh G, Morgan D, LeMay L, Robinson J, Mock J. Noninvasive pulse wave analysis for the early detection of vascular disease. Hypertension. 1995;26:503–508. doi:10.1161/01.HYP.26.3.503.
23. Cohn JN. Arterial stiffness, vascular disease, and risk of cardiovascular events. Circulation. 2006;113:601–603. doi:10.1161/CIRCULATIONAHA.105.600866.
24. Nichols W, O'Rourke M, McDonald D. McDonald's Blood Flow in Arteries: Theoretical, Experimental and Clinical Principles. 6th ed. London: Hodder Arnold; 2011.
25. Prisant LM, Pasi M, Jupin D, Prisant ME. Assessment of repeatability and correlates of arterial compliance. Blood Press Monit. 2002;7:231–235.
26. Zimlichman R, Shargorodsky M, Boaz M, Duprez D, Rahn KH, Rizzoni D, Payeras AC, Hamm C, McVeigh G. Determination of arterial compliance using blood pressure waveform analysis with the CR-2000 system: Reliability, repeatability, and establishment of normal values for healthy European population – The Seven European Sites Study (SESS). Am J Hypertens. 2005;18:65–71. doi:10.1016/j.amjhyper.2004.08.013.
27. Nunan D, Donovan G, Jakovljevic DG, Hodges LD, Sandercock GR, Brodie DA. Validity and reliability of short-term heart-rate variability from the Polar S810. Med Sci Sports Exerc. 2009;41:243–250. doi:10.1249/MSS.0b013e318184a4b1.
28. Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Circulation. 1996;93;1043–65. doi:10.1161/01.CIR.93.5.1043.
29. Shin JH, Lee Y, Kim SG, Choi BY, Lee HS, Band SY. The beneficial effects of Tai Chi exercise on endothelial function and arterial stiffness in elderly women with rheumatoid arthritis. Arthritis Res Ther. 2015;17:380. doi:10.1186/s13075-015-0893-x.
30. Grey E, Bratteli C, Glasser SP, Alinder C, Finkelstein SM, Lindgren BR, Cohn JN. Reduced small artery but not large artery elasticity is an independent risk marker for cardiovascular events. Am J Hypertension. 2003;16:265–269. doi:10.1016/S0895-7061(02)03271-5.
31. Kim YB, Park KY, Chung PW, Kim JM, Moon HS, Youn YC. Brachial-ankle pulse wave velocity is associated with both acute and chronic cerebral small vessel disease. Atherosclerosis. 2016;245:54–59. doi:10.1016/j.atherosclerosis.2015.12.006.
32. Sakuragi S, Abhayaratna WP. Arterial stiffness: Methods of measurement, physiologic determinants and prediction of cardiovascular outcomes. Int J Cardiol. 2010;138:112–118. doi:10.1016/j.ijcard.2009.04.027.
33. Wang JS, Lan C, Chen SY, Wong MK. Tai Chi Chuan training is associated with enhanced endothelium-dependent dilation in skin vasculature of healthy older men. J Am Geriatr Soc. 2002;50:1024–1030. doi:10.1046/j.1532-5415.2002.50256.x.
34. Pan X, Zhang Y, Tao S. Effects of Tai Chi exercise on blood pressure and plasma levels of nitric oxide, carbon monoxide and hydrogen sulfide in real-world patients with essential hypertension. Clin Exp Hypertens. 2015;37:8–14. doi:10.3109/10641963.2014.881838.

35. Zheng G, Li S, Huang M, Liu F, Tao J, Chen L. The effect of Tai Chi training on cardiorespiratory fitness in healthy adults: A systematic review and meta-analysis. PLoS ONE. 2015;10:e0117360. doi:10.1371/journal.pone.0117360.
36. Sörös P, Hachinski V. Cardiovascular and neurological causes of sudden death after ischaemic stroke. Lancet Neurol. 2012;11:179–188. doi:10.1016/S1474-4422(11)70291-5.