THE GERONTOLOGICAL SOCIETY OF AMERICA®

Journals of Gerontology: Medical Sciences
cite as: *J Gerontol A Biol Sci Med Sci*, 2019, Vol. 74, No. 9, 1497–1503
doi:10.1093/gerona/glz018
Advance Access publication December 21, 2018

OXFORD

Research Article

Comparison of Treadmill Trip-Like Training Versus Tai Chi to Improve Reactive Balance Among Independent Older Adult Residents of Senior Housing: A Pilot Controlled Trial

Jessica Aviles, MS,[1] Leigh J. Allin, MS,[1] Neil B. Alexander, MD,[2,3] Jennifer Van Mullekom, PhD,[4] Maury A. Nussbaum, PhD,[1,5] and Michael L. Madigan, PhD[1,5,*]

[1]Department of Biomedical Engineering and Mechanics, Virginia Tech, Blacksburg. [2]Division of Geriatric and Palliative Medicine, Department of Internal Medicine, University of Michigan, Ann Arbor. [3]Ann Arbor Veterans Affairs Health Care System Geriatric Research Education and Clinical Center, Michigan. [4]Department of Statistics and [5]Grado Department of Industrial & Systems Engineering, Virginia Tech, Blacksburg.

*Address correspondence to: Michael L. Madigan, PhD, Department of Industrial & Systems Engineering, Virginia Tech, (0118) 1145 Perry Street, Blacksburg, VA 24061-0118. E-mail: mlm@vt.edu

Received: June 27, 2018; Editorial Decision Date: December 27, 2018

Decision Editor: Anne Newman, MD, MPH

Abstract

Background: There is growing interest in using perturbation-based balance training to improve the reactive response to common perturbations (eg, tripping and slipping). The goal of this study was to compare the efficacy of treadmill-based reactive balance training versus Tai Chi performed at, and among independent residents of, older adult senior housing.
Methods: Thirty-five residents from five senior housing facilities were allocated to either treadmill-based reactive balance training or Tai Chi training. Both interventions were performed three times per week for 4 weeks, with each session lasting approximately 30 minutes. A battery of balance tests was performed at baseline, and again 1 week, 1 month, 3 months, and 6 months post-training. The battery included six standard clinical tests of balance and mobility, and a test of reactive balance performance.
Results: At baseline, no significant between-group differences were found for any balance tests. After training, reactive balance training participants had better reactive balance than Tai Chi participants. Maximum trunk angle was 13.5° smaller among reactive balance training participants 1 week after training ($p = .01$), and a reactive balance rating was 24%–31% higher among reactive balance training participants 1 week to 6 months after training ($p < .03$). Clinical tests showed minimal differences between groups at any time point after training.
Conclusion: Trip-like reactive balance training performed at senior housing facilities resulted in better rapid balance responses compared with Tai Chi training.

Keywords: Balance-biomechanics, Exercise, Falls, Gait-biomechanics

Adults aged 65 and older in the United States fell an estimated 29 million times in 2014, resulting in an estimated 7 million injuries (1), and costing an estimated $50 billion, annually (2). The number of annual falls is expected to increase due to growth of the older adult population, and may even be increasing independent of this demographic shift (3).

A growing number of studies are using task-specific, perturbation-based, reactive balance training (RBT) to improve the reactive response to common perturbations, such as tripping and slipping while walking (4–6). This training approach leverages the principle of training specificity (7), which indicates that the closer training mimics the activity of interest, the more the training will improve performance of the activity of interest. RBT involves repeatedly exposing individuals to realistic simulated trips or slips in a safe, controlled manner. Through repetition, individuals are able to improve their reactive balance in response to such perturbations, and reduce the risk of prospective falls (4).

Three recent reviews compiled studies investigating RBT versus nonperturbation control interventions on fall incidence among older adults (8–10). Diverse control interventions were identified by these reviews, including: walking (11); flexibility and relaxation training (12); strength training (13); voluntary stepping exercises (14); multi-component physical therapy involving strength and flexibility training; standing balance and/or gait training (15,16), stretching and controlled upper and lower limb volitional movements while supine, sitting, and standing (17); and no exercise (4). To our knowledge, however, no studies have compared RBT to Tai Chi training, the latter of which is an evidence-based exercise program that has been demonstrated to reduce fall risk (and is recommended by the Centers for Disease Control and Prevention (18) and the National Council on Aging (19)). Moreover, prior studies that included trip-like or slip-like RBT (4,6,11,20) were performed in a research setting. Implementing any fall-risk reducing exercise program would likely be enhanced by providing the training on-site where older adults reside, such as in senior housing, thereby facilitating participation in and overall impact of the program.

Contrasting RBT and Tai Chi highlights a key difference in their approach to fall-risk reduction training. RBT trains the abrupt, dynamic, and specific response to common perturbations such as tripping. In contrast, Tai Chi involves slower, more measured and volitional movements. Based upon the principle of training specificity, RBT is more likely than Tai Chi to improve performance on reactive balance tests. Tai Chi, however, is more qualitatively similar to clinical tests of balance and mobility that are predictive of fall risk, and are thus more likely to improve performance on these tests than RBT.

The goal of this pilot controlled trial was to compare the efficacy of RBT versus Tai Chi performed at, and among independent residents of, older adult senior housing. This RBT is a form of task-specific, perturbation-based balance training involving trip-like perturbations on a modified treadmill (4,5). Based on evidence of fall risk reduction among older adults (21) and wide implementation, Tai Chi was chosen as an active control training exercise. Outcome measures included reactive balance tests involving trip-like perturbations on the modified treadmill, and standard clinical tests of balance and mobility. We tested two hypotheses, both of which were motivated by the principle of training specificity. We hypothesized that participants randomized to RBT would show better performance on reactive balance tests compared with participants randomized to Tai Chi. We also hypothesized that participants randomized to Tai Chi would show better performance on clinical tests of balance and mobility compared with participants randomized to RBT. The work presented here was meant to be a pilot study to aid in planning a larger, future follow-up study. The long-term goal of this work is to demonstrate the value of RBT over Tai Chi for preventing falls resulting from sudden, external perturbations.

Methods

Participants

This study (NCT02551666 at clinicaltrials.gov) was approved by the university Institutional Review Board, and written consent was obtained from all participants before participation. Inclusion criteria required participants to: (a) be at least 70 years old and independent residents of senior housing facilities; (b) walk without the aid of an assistive device; (c) have a bone mineral density of the proximal hip of $t \geq -2.0$, obtained from Dual Energy X-ray Absorptiometry (Hologic, Inc., Hologic Discovery W QDR series, Waltham, MA); (d) score at least 24 on the standardized mini-mental state exam (22); (e) pass a medical screening by a physician that excluded individuals with major unstable cardiopulmonary disease, previous or current smokers, or individuals with other progressive or unstable medical conditions that could account for possible imbalance and falls; (f) must not be in physical therapy; (g) must not perform more than 150 min/wk of moderate to vigorous aerobic activity, and (h) not have participated in Tai Chi classes. Participants were recruited through oral presentations and flyers at seven senior housing facilities in collaboration with facility staff.

Participants were allocated to RBT or Tai Chi using a computer-based algorithm to minimize differences in key confounders. Minimization, which is an adaptive randomization, stipulates that the next participant to enter the trial is assigned to a group that minimizes group imbalance on selected variable(s) (23). Using this scheme, participants were allocated to the training groups while balancing between groups: age (70–79 or 80 and older), gender (male or female), and baseline reactive balance rating score (0, 1, or 2, see below). The targeted sample size ($p < .05$, $\beta = .85$) was $n = 15$ in each group, with the effect size (Cohen's $d = 0.8$) conservatively estimated to be half of that reported for maximum trunk angle after a single session of treadmill training (11).

A total of 151 participants expressed initial interest, and 116 were excluded because they did not satisfy all inclusion criteria, declined to participate, or had other personal circumstances that precluded their participation (Figure 1). The remaining 35 independent-living residents were allocated to either RBT or Tai Chi according to the minimization scheme. Three RBT participants discontinued the study during the training (two of these due to medical conditions unrelated to the study). Because recruitment occurred in stages as additional retirement communities participated in the study, and because these three participants discontinued training in the middle third of our recruitment period, these participants who discontinued were removed from the minimization scheme, and subsequent group

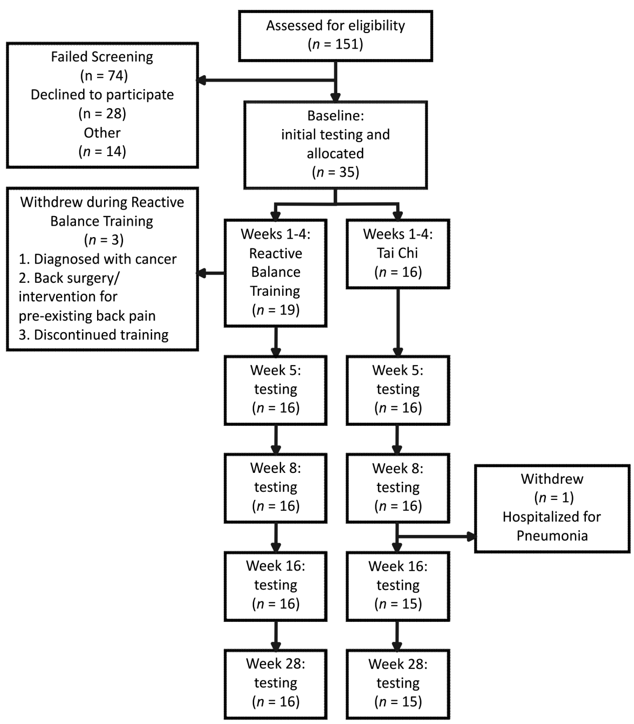

Figure 1. Study flow diagram. For each stage, *n* indicates the number of participants who completed that part of the protocol.

allocation accounted for their removal. One Tai Chi participant discontinued the study during the post-training follow-up, also due to a medical condition unrelated to the study. Participant recruitment, screening, and testing took place from September 2015 to July 2017.

Assessments

Participants completed a battery of balance tests before the assigned intervention (baseline), as well as 1 week (Week 5), 1 month (Week 8), 3 months (Week 16), and 6 months (Week 28) after training. All tests were performed by an investigator (L.J.A.) who was blinded to participants' group assignment. The test battery included standard clinical tests and a reactive balance test, as described subsequently.

Clinical tests

Six fall-risk relevant tests of balance, mobility, and balance confidence were included to provide a broad evaluation of stepping ability, standing balance, and overall mobility. These tests included: timed-up-and-go test (TUG) as a simple measure of mobility (24); unipedal stance time as a measure sensitive to balance training and fall risk (25); maximum step length as a predictor of fall-risk relevant mobility (26); Berg Balance Scale as a measure of static balance and fall-risk (27); Performance-Oriented Mobility Assessment (POMA) as a measure of gait and balance (28); and Activities-specific Balance Confidence Scale (ABC) as a measure of fear of falling (23).

Reactive balance tests

Each testing session included a reactive balance test (29). Briefly, participants stood on a modified treadmill (Freemotion 800, Freemotion Fitness, Logan, UT) with the treadmill belt speed at zero, and facing forward. The treadmill belt was then accelerated posteriorly to a selected speed within approximately 40 msec to induce a forward loss of balance. Participants were instructed to react naturally, and to attempt to establish a stable walking pattern. The treadmill belt speed was maintained until one of two outcomes occurred: the participant established a stable gait pattern for several strides, or the participant received substantial support from a fall prevention harness or spotters standing next to her/him. Two perturbations were performed at each of three speeds (0.8, 1.6, and 2.4 mph) to provide three levels of difficulty. Two perturbations at 0.8 mph in the reverse belt direction were also performed to reduce anticipation, but were not included in characterizing reactive balance. Participants wore a fall protection harness, supported by an overhead gantry, to prevent knee or hand contact with the treadmill in the event of an unsuccessful attempt to recover balance. Before each perturbation, a slender, rectangular foam block (4 × 4 cm cross section) was positioned 3–7 cm in front of the toes to elicit an initial step over an obstacle, similar to that needed after a trip. Potential anticipatory postural adjustments were not measured, but were discouraged by repeatedly reminding subjects to stand up straight and look straight ahead before perturbations.

The primary outcome measure was the maximum forward trunk angle over the 1.2 seconds immediately after perturbation onset, with trunk angle sampled at 128 Hz using an inertial measurement unit (APDM, Inc., Portland, OR) worn inferior to the suprasternal notch with a shoulder strap. Although related, this differs from trunk angle or angular velocity at completion of the first recovery step reported in other trip-related studies (30,31). Three measures of stepping characteristics were also determined from video recordings of each treadmill perturbation, including the length of initial step over the block (step length), time from the onset of treadmill movement to liftoff of initial recovery step (liftoff time), and time from the onset of treadmill movement to touchdown of initial step over the block (touchdown time). These measures were selected based upon their use in prior studies to assess reactive balance after treadmill perturbations (32,33), and because they have been shown to differ between successful and failed recoveries after trip-like perturbations (33). Participant inability to complete treadmill trials at 2.4 mph, or unwillingness to continue, resulted in a large percentage of missing data describing stepping characteristic (ranging from 31% of liftoff time to 69% of maximum trunk angle values), and thus these measures were not determined for trials at 2.4 mph. A reactive balance rating score was also determined (29). This score, which was not an a priori outcome measure developed before the start of this trial, is based upon group-blinded investigators viewing video recordings of each perturbation during reactive balance tests, and rating them on a three-level scale in terms of both the quality of the stepping response and the amount of support provided by the fall prevention harness and/or spotters standing next to the participant (see Supplementary Material for additional details). These ratings were combined across both trials at speeds of 0.8, 1.6, and 2.4 mph, and provided a rating score that ranged from 0 to 12 (best). Moreover, maximum trunk angle, step length, and touchdown time were excluded from further analysis if the amount of support provided by the fall prevention harness and/or spotters standing next to the participant was rated as substantial (Supplementary Material) to avoid any such support from confounding these measures.

Falls assessment

The number of all-cause falls and trip-induced falls outside of testing and training were recorded over the 6 months after the intervention (from Week 5 to Week 28). Such falls were quantified through telephone calls made every 2 weeks to each participant. A fall was defined as unintentionally coming to rest on the ground or lower level, not caused by loss of consciousness or overwhelming hazard (34).

Interventions

Both RBT and Tai Chi interventions involved twelve 30-minute sessions, scheduled three times per week for 4 weeks. Participants were required to complete at least nine sessions (75% of the total 12) to be considered to be adherent to the protocol; mean RBT and Tai Chi attendance was 91% and 94%, respectively. Sixteen of 19 participants who were placed in RBT, and all 16 in the Tai Chi, met the minimum number of sessions required to be adherent and were included in the analysis. Each RBT session involved one participant at a time, and up to 40 treadmill perturbations with rest breaks every 10 perturbations. Perturbations were similar to those during reactive balance tests, with perturbations varying in speed from 0.5 to 2.4 mph for backward belt movement, and set to 0.5 mph for forward belt movement. Our goal in the training was to increase speeds progressively during each session and across sessions to continue to challenge participants as their performance improved, while also unexpectedly varying speeds and direction to maintain variability throughout training. Each Tai Chi session was led by an instructor with experience in leading community-based Tai Chi for older adults, used 12 unique sequences from the Yang Short Form, and was conducted in groups of a mean size of 5.3 participants. All testing and intervention sessions were performed on-site at the senior housing facilities.

Data Analyses

Clinical and reactive balance measures were compared between RBT and Tai Chi groups using a mixed model (SAS PROC MIXED procedure, SAS Institute, Inc., Cary NC) that accounted for fixed and random effects, and within-participant correlation. For the clinical tests, fixed effects of intervention (RBT or Tai Chi), time (1 week, 1 month, 3 months, or 6 months post-intervention), and intervention × time were included, as well as covariates of baseline (preintervention) performance, age, gender, and baseline reactive balance rating score. For the reactive balance measures, fixed effects of intervention, time, speed, and all two-factor interactions were included, along with the same covariates noted above. Hierarchical models were used in analyzing reactive balance measures to account for the two levels of repeated measures (time and speed) and the two replications of each time-speed combination. Only participants who were adherent to the protocol (completed at least nine of 12 training sessions) were included in the analysis. a priori simple effects investigated differences between intervention groups at each time point to address our hypotheses, and the Tukey–Kramer method was used to adjust for Type I error rate, with a significance level of $p \leq .05$. Differences in categorical variables between groups were evaluated using Fisher's Exact Test.

Results

At baseline, no significant between-group differences were present in demographics, clinical test scores, reactive balance measures, or fall history (Tables 1 and 2).

After training, RBT participants exhibited significantly better reactive balance compared with Tai Chi participants. Maximum trunk angle was 13.5° smaller among RBT participants 1 week after training ($p = .01$ for both speeds combined), but did not differ significantly between RBT and Tai Chi groups at any other time point ($p > .07$). Step length ($p > .23$), liftoff time ($p > .36$), and touchdown time ($p > .56$) did not differ significantly between the two training groups at any time point. Reactive balance rating was statistically higher among RBT participants at multiple time points post-training (Figure 2), including 24% higher at 1 week ($p = .02$), 31% higher at 1 month after training ($p = .02$), and 28% higher at 6 months ($p = .03$).

Clinical tests showed no statistical differences between RBT participants and Tai Chi participants (aside from greater improvement in POMA among Tai Chi participants at Week 5; $p = .04$) at any time point after training. Regarding self-reported falls after training (from Week 5 to 28), of the four RBT and five Tai Chi all-cause falls, trip-related falls were reported by only one RBT and one Tai Chi participant. These small samples precluded any meaningful analysis.

Three RBT participants withdrew during training due to a diagnosis of cancer, back surgery for preexisting back pain, and preference for Tai Chi. It was not clear whether the preexisting back pain was aggravated during RBT. Some subjects reported anxiousness toward the treadmill (particularly higher speeds), some soreness in the lower limbs, and some soreness/bruising near the shoulders due to harness support.

Table 1. Participant Characteristics at Baseline, Including Demographic Information, Clinical Test Scores, and Fall History

	Reactive Balance Training	Tai Chi Training	*p* Value
Number of participants (women)	19 (13)	16 (11)	
Age (years)	80.9 (6.2)	82.6 (4.5)	.36
Body mass index (kg/m^2)	28.6 (5.3)	30.8 (4.5)	.19
Timed up and go (s)	12.9 (4.5)	14.8 (6.0)	.31
Unipedal stance time (s)	5.7 (6.4)	4.0 (3.2)	.31
Maximum step length (in)	20.5 (5.7)	18.1 (5.2)	.21
Berg Balance Scale	47.3 (4.3)	44.5 (5.6)	.12
Performance Oriented Mobility Assessment	23.7 (2.8)	22.8 (3.7)	.42
Activities-specific Balance Confidence Scale (%)	74.0 (14.1)	76.2 (16.3)	.68
% reporting falls with injury in the past year	5.3%	31.3%	.07
% reporting 2 or more falls in the past year	10.5%	31.3%	.21

Note: Entries other than the number of participants given as means (*SD*).

Table 2. Reactive Balance Measures at Baseline

	Reactive Balance Training	Tai Chi Training	*p* Value
Number of participants (women)	19 (13)	16 (11)	
Reactive balance rating	4.8 (3.5)	4.3 (2.0)	.98
Stepping kinematics at 0.8 mph			
Step length (m)	0.51 (0.09)	0.49 (0.06)	.77
Liftoff time (s)	0.39 (0.05)	0.40 (0.08)	.68
Touchdown time (s)	0.73 (0.10)	0.70 (0.08)	.86
Maximum trunk angle (°)	23.9 (10.6)	18.8 (9.0)	.23
Stepping kinematics at 1.6 mph			
Step length (m)	0.56 (0.11)	0.61 (0.10)	.77
Liftoff time (s)	0.35 (0.06)	0.36 (0.10)	.68
Touchdown time (s)	0.59 (0.07)	0.61 (0.09)	.86
Maximum trunk angle (°)	28.4 (10.4)	29.7 (14.1)	.23

Note: Entries other than the number of participants given as means (*SD*).

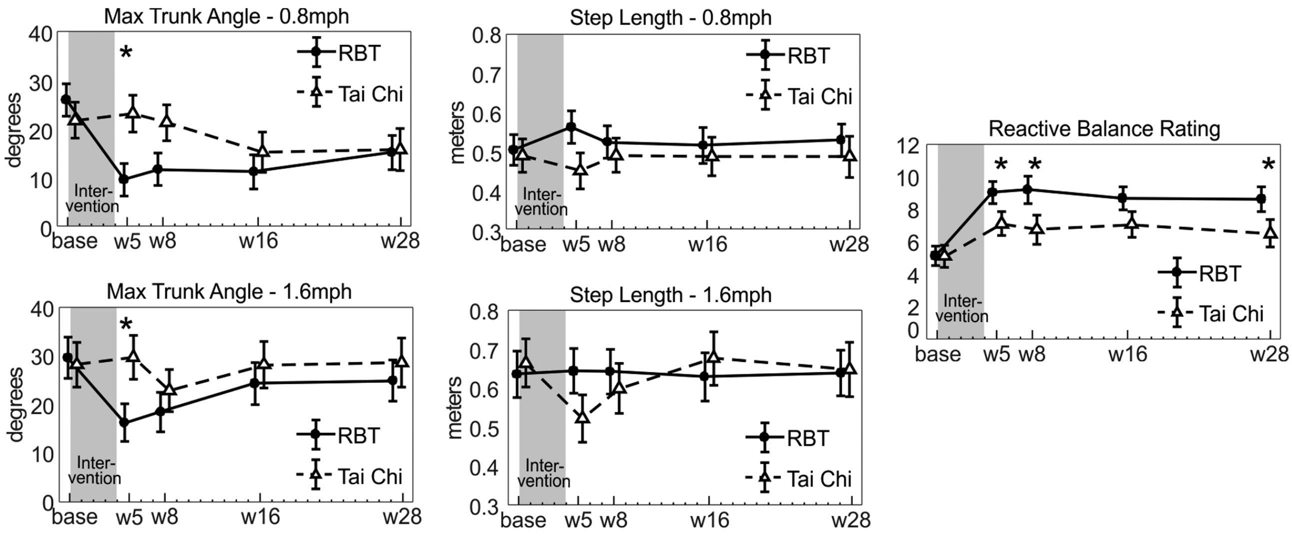

Figure 2. Maximum trunk angle, step length, and reactive balance rating at baseline (base) before the 4-week intervention, Week 5 (w5), Week 8 (w8), Week 16 (w16), and Week 28 (w28). Reactive balance rating ranges from 0 to 12 (best). Values illustrated are least square means, errors bars are standard errors, and asterisk indicates a significant difference ($p \leq .05$) between training groups at a given time point. Sample size at each time point was the number of participants who completed at least 9 of 12 training sessions. For RBT participants, this was $n = 16$ for all time points. For Tai Chi participants, this was $n = 16$ for time points of baseline through Week 8, and $n = 15$ for time points of Week 16 and Week 28.

Discussion

The goal of this study was to compare the efficacy of RBT versus Tai Chi performed at, and among independent residents of, older adult senior housing facilities. To our knowledge, this is the first study that compared RBT to Tai Chi, the latter an evidence-based fall intervention risk reduction exercise program recommended by the Centers for Disease Control and Prevention (18) and the National Council on Aging (19). Also unique to this study is that training was performed at senior housing facilities, thereby demonstrating its feasibility as an on-site balance training exercise intervention, and providing a model of how to make fall reduction training more acceptable to residents. Also of note is that baseline clinical tests suggested that many participants had an increased fall risk based on established fall risk cutoffs for the timed-up-and-go tests (13.5 seconds) (33), unipedal stance time (less than 5 seconds) (24), Berg balance scale (less than 45) (26), and POMA (24 or lower) (27). We hypothesized that participants randomized to RBT would show better performance on reactive balance tests compared with participants randomized to Tai Chi. This hypothesis was supported, in that RBT participants showed better reactive balance post-intervention despite there being no differences between groups at baseline. Moreover, RBT participants retained an improved reactive balance rating compared with Tai Chi participants, notably at 6 month follow-up. We also hypothesized that participants randomized to Tai Chi would show better performance on clinical tests of balance and mobility compared with participants randomized to RBT. This hypothesis was not supported, in that Tai Chi participants showed no postintervention differences from RBT participants in clinical tests of balance and mobility (other than better performance in POMA among Tai Chi participants at Week 5).

Maximum trunk angle was the only kinematic measure that improved after intervention and which differed statistically between groups. This finding provides insight on the biomechanical mechanism by which trip-like RBT can reduce trip-induced falls, and supports the importance of the trunk in responding to trip-like perturbations noted elsewhere (30). Moreover, after the initial reduction at Week 5 due to RBT, maximum trunk angle appeared to return toward baseline over the 23-week follow-up period, suggesting a possible loss of retention over time (Figure 2). Interestingly, reactive balance rating was higher among RBT participants than Tai Chi participants at 1 week, 1 month, and 6 months after intervention. We believe these differing trends between maximum trunk angle and reactive balance rating were due to the reactive balance rating providing a more holistic evaluation rather than a more narrow single kinematic measure. Using reactive balance to avoid a fall after a trip-like postural perturbation has multiple requisites, which likely cannot be adequately evaluated with a single kinematic measure (ie, maximum trunk angle). These requisites include arresting trunk motion, maintaining adequate hip height to allow continued stepping, and expanding the base of support by stepping so the ground reaction force can contribute to decelerating the forward fall (33,35). The stepping response and support components of the reactive balance rating evaluate aspects of reactive balance that directly related to all three of these requisites. As such, the rating may be more sensitive to overall reactive balance than a single kinematic measure, and may eventually be used in a clinical setting.

RBT elicited clinically relevant improvements in trunk control after trip-like perturbations. Maximum trunk angle among RBT participants was 13.5° smaller 1 week after intervention compared with baseline. This is comparable to the 14°–21° smaller trunk angles reported during successful versus failed recoveries from both similar treadmill perturbations (31,33) and laboratory-induced trips while walking (36). Trunk angle (and trunk angular velocity, not investigated here) was found earlier to be the strongest discriminator between falls and recoveries after trip-like treadmill perturbations when compared with other kinematic response measures (31), supporting the importance of trunk control in these reactive responses. A reduction in max trunk angle, along with other improvements in reactive balance after task-specific perturbation-based balance training, has been attributed to improvements in the complex, highly coordinated, and time-critical muscle activation timing and magnitude that modulates the multiarticular response to the perturbations (37). However, we are not aware of any studies that have investigated changes in these aspects of the neuromuscular response after trip-like reactive balance training on a treadmill.

Clinical tests predictive of fall risk were not found to be sensitive to RBT. It is possible that these clinical tests do not adequately assess the reactive balance response after a perturbation. Evaluating RBT-induced balance improvement may require kinematic measures more directly related to fall avoidance postperturbation. For example, averting a fall after a trip or trip-like perturbation requires arresting trunk motion, maintaining adequate hip height to allow continued stepping, and stepping to expand the base of support (33,35,36). The reactive balance rating provides a clinical analogue to these measures (29), which, together with maximum trunk angle, improved with RBT. Moreover, as evidence of the specificity of RBT, these reactive measures did not change with Tai Chi. Overall, the clinical tests used here likely reflected general functional capabilities that associate with fall risk, but may not be responsive to short-term interventions. Clinical tests may be more predictive of fall risk as a result of general decline of physical function, gait, and standing balance, while reactive balance measures after trip-like perturbations investigated here may better predict trip-induced fall risk. It should also be noted that the timed-up-and-go test (due to low sensitivity) and Berg balance scale (due to ceiling effects) can have limited ability to predict falls among independent older adults (38,39).

Sherrington and colleagues (40) acknowledged no clear guidance from the literature on the dosage of exercise required to reduce falls, but did find more robust effects among exercises with a dosage of at least 50 hours, and that the benefits of exercise on falls are rapidly lost when exercise ceases. Rosenblatt and colleagues (4) reported a lower fall rate outside the lab among older women after four sessions involving trip-like treadmill perturbations more than 2 weeks. Grabiner and colleagues (5) reported a lower fall rate and improved reactive balance among older women when exposed to a laboratory-induced trip after 4–10 sessions involving trip-like treadmill perturbations over approximately four weeks. The present study achieved meaningful improvements in reactive balance that persisted for up to 6 months after 12 training sessions totaling 6 hours in dosage. This seemingly higher potency is likely due, at least in part, to our outcome not being falls but reactive balance responses. However, the specificity of training used here may offer higher potency than interventions with less task specificity, at least for trip-induced falls.

Several limitations of this study warrant attention. First, our sample size was not sufficient to investigate falls as an outcome. The data from this pilot trial can be used to plan a larger follow-up study with falls as an outcome. Second, we acknowledge that there could have been a training effect among Tai Chi participants due to their repeated exposure to perturbations during assessments before and after the intervention. Nevertheless, this limitation is somewhat inevitable when studying task-specific training (ie, when training closely matches outcome assessments), with repeated measurements to investigate retention. Any such training benefits among the control group would effectively increase the burden of proof placed on RBT, in terms of what benefits must be found to demonstrate an improvement compared with controls. Third, our use of twelve 30-minute sessions of Tai Chi over 4 weeks was less than that used in other studies that have demonstrated beneficial effects of Tai Chi on falls (18), and thus it may not have been sufficient to improve reactive balance or clinical test measures. We cannot discount the possibility that increasing the dosage of Tai Chi training could have resulted in larger improvements in reactive balance among Tai Chi participants (although this would not support our hypothesis that the principle of training specificity limits transfer from Tai Chi to RBT, rather than training dosage). However, we chose the specific approach here to match the training dose received by RBT participants. Fourth, RBT required some accommodation to past participant experience. Some participants had little to no treadmill exercise experience, and these participants completed 1–2 additional sessions before the start of the intervention to learn to comfortably walk on the treadmill. Fifth, while it has not been established who can participate safely and benefit from this training, we suspect that RBT is likely not appropriate for all older adults given the possibility (but low probability) of injury and physical demands required to react quickly to the sudden, large-scale postural perturbations that are involved. Sixth, participants may learn to rely on the harness and spotters in response to perturbations, yet these are not available during real-world loss of balance. However, these are required, at least for now, to safely train participants.

In conclusion, treadmill-based reactive balance training was performed on-site at senior housing facilities and among residents identified as at an elevated fall risk, and resulted in better rapid balance responses compared with Tai Chi training. These results support the feasibility of performing RBT on-site, without the use of typical laboratory equipment. Larger controlled studies are needed to evaluate the relative effectiveness of these two types of training on fall risks, particularly falls that involve a trip or slip.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences* online.

Funding

This work was supported by the National Institutes of Health (R21 AG045723 to MLM, P30 AG024824 to NBA); National Science Foundation (HRD-1502335); Office of Research and Development of the Department of Veterans Affairs; and the Michigan Institute for Clinical and Health Research (UL1TR000433).

Acknowledgments

We thank Achu Byju, Tim Ward, Debra Strasburg, and Bonnie Zollinger for their contributions to this project, and the staff at the following senior communities in Bryan/College Station, TX: Watercrest at Bryan, Crestview, Carriage Inn, Waldenbrooke Estates, Terrace Pines, Villas of Rock Prairie, and The Waterford at College Station.

Conflict of interest statement

None reported.

References

1. Bergen G, Stevens MR, Burns ER. Falls and fall injuries among adults aged ≥65 years—United States, 2014. *MMWR Morb Mortal Wkly Rep.* 2016;65:993–998. doi:10.15585/mmwr.mm6537a2
2. Florence CS, Bergen G, Atherly A, Burns E, Stevens J, Drake C. Medical costs of fatal and nonfatal falls in older adults. *J Am Geriatr Soc.* 2018;66:693–698. doi:10.1111/jgs.15304

3. Cigolle CT, Ha J, Min LC, Lee PG, Gure TR, Alexander NB, et al. The epidemiologic data on falls, 1998–2010: more older Americans report falling. *JAMA Intern Med*. 2015;175:443–445. doi:10.1001/jamainternmed.2014.7533
4. Rosenblatt NJ, Marone J, Grabiner MD. Preventing trip-related falls by community-dwelling adults: a prospective study. *J Am Geriatr Soc*. 2013;61:1629–1631. doi:10.1111/jgs.12428
5. Grabiner MD, Bareither ML, Gatts S, Marone J, Troy KL. Task-specific training reduces trip-related fall risk in women. *Med Sci Sports Exerc*. 2012;44:2410–2414. doi:10.1249/MSS.0b013e318268c89f
6. Bhatt T, Yang F, Pai YC. Learning to resist gait-slip falls: long-term retention in community-dwelling older adults. *Arch Phys Med Rehabil*. 2012;93:557–564. doi:10.1016/j.apmr.2011.10.027
7. Schmidt RA, Lee TD. *Motor Control and Learning: A Behavioral Emphasis*. 5th ed. Champaign, IL: Human Kinetics; 2011.
8. Okubo Y, Schoene D, Lord SR. Step training improves reaction time, gait and balance and reduces falls in older people: a systematic review and meta-analysis. *Br J Sports Med*. 2017;51:586–593. doi:10.1136/bjsports-2015-095452
9. Mansfield A, Wong JS, Bryce J, Knorr S, Patterson KK. Does perturbation-based balance training prevent falls? Systematic review and meta-analysis of preliminary randomized controlled trials. *Phys Ther*. 2015;95:700–709. doi:10.2522/ptj.20140090
10. Gerards MHG, McCrum C, Mansfield A, Meijer K. Perturbation-based balance training for falls reduction among older adults: current evidence and implications for clinical practice. *Geriatr Gerontol Int*. 2017;17:2294–2303. doi:10.1111/ggi.13082
11. Bieryla KA, Madigan ML, Nussbaum MA. Practicing recovery from a simulated trip improves recovery kinematics after an actual trip. *Gait Posture*. 2007;26:208–213. doi:10.1016/j.gaitpost.2006.09.010
12. Mansfield A, Peters AL, Liu BA, Maki BE. Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. *Phys Ther*. 2010;90:476–491. doi:10.2522/ptj.20090070
13. Shen X, Mak MK. Technology-assisted balance and gait training reduces falls in patients with Parkinson's disease: a randomized controlled trial with 12-month follow-up. *Neurorehabil Neural Repair*. 2015;29:103–111. doi:10.1177/1545968314537559
14. Maki BE, Cheng KC, Mansfield A, et al. Preventing falls in older adults: new interventions to promote more effective change-in-support balance reactions. *J Electromyogr Kinesiol*. 2008;18:243–254. doi:10.1016/j.jelekin.2007.06.005
15. Lurie JD, Zagaria AB, Pidgeon DM, Forman JL, Spratt KF. Pilot comparative effectiveness study of surface perturbation treadmill training to prevent falls in older adults. *BMC Geriatr*. 2013;13:49. doi:10.1186/1471-2318-13-49
16. Shimada H, Obuchi S, Furuna T, Suzuki T. New intervention program for preventing falls among frail elderly people: the effects of perturbed walking exercise using a bilateral separated treadmill. *Am J Phys Med Rehabil*. 2004;83:493–499. doi:10.1097/01.PHM.0000130025.54168.91
17. Smania N, Corato E, Tinazzi M, et al. Effect of balance training on postural instability in patients with idiopathic Parkinson's disease. *Neurorehabil Neural Repair*. 2010;24:826–834. doi:10.1177/1545968310376057
18. Stevens JA, Burns ER. *A CDC Compendium of Effective Fall Interventions: What Works for Community-Dwelling Older Adults*. 3rd ed. Atlanta, GA: National Center for Injury Prevention and Control; 2015.
19. National Council on Aging. *Evidence-based falls prevention programs*. 2018. https://www.ncoa.org/healthy-aging/falls-prevention/falls-prevention-programs-for-older-adults-2/. Accessed January 25, 2019.
20. Pai YC, Bhatt T, Yang F, Wang E. Perturbation training can reduce community-dwelling older adults' annual fall risk: a randomized controlled trial. *J Gerontol A Biol Sci Med Sci*. 2014;69:1586–1594. doi:10.1093/gerona/glu087
21. Huang ZG, Feng YH, Li YH, Lv CS. Systematic review and meta-analysis: Tai Chi for preventing falls in older adults. *BMJ Open*. 2017;7:e013661. doi:10.1136/bmjopen-2016-013661
22. Folstein MF, Folstein SE, McHugh PR. "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. *J Psychiatr Res*. 1975;12:189–198. doi:10.1016/0022-3956(75)90026-6
23. Powell LE, Myers AM. The Activities-specific Balance Confidence (ABC) Scale. *J Gerontol A Biol Sci Med Sci*. 1995;50A:M28–M34. doi:10.1093/gerona/50A.1.M28
24. Podsiadlo D, Richardson S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. *J Am Geriatr Soc*. 1991;39:142–148. doi:10.1111/j.1532–5415.1991.tb01616.x
25. Vellas BJ, Wayne SJ, Romero L, Baumgartner RN, Rubenstein LZ, Garry PJ. One-leg balance is an important predictor of injurious falls in older persons. *J Am Geriatr Soc*. 1997;45:735–738. doi:10.1111/j.1532–5415.1997.tb01479.x
26. Cho BL, Scarpace D, Alexander NB. Tests of stepping as indicators of mobility, balance, and fall risk in balance-impaired older adults. *J Am Geriatr Soc*. 2004;52:1168–1173. doi:10.1111/j.1532-5415.2004.52317.x
27. Berg KO, Wood-Dauphinee SL, Williams JI, Maki B. Measuring balance in the elderly: validation of an instrument. *Can J Public Health*. 1992;83(suppl 2):S7–S11.
28. Tinetti ME. Performance-oriented assessment of mobility problems in elderly patients. *J Am Geriatr Soc*. 1986;34:119–126. doi:10.1111/j.1532–5415.1986.tb05480.x
29. Madigan ML, Aviles J, Allin LJ, Nussbaum MA, Alexander NB. A reactive balance rating method that correlates with kinematics after trip-like perturbations on a treadmill and fall risk among residents of older adult congregate housing. *J Gerontol A Biol Sci Med Sci*. 2018;73:1222–1228. doi:10.1093/gerona/gly077
30. Grabiner MD, Donovan S, Bareither ML, et al. Trunk kinematics and fall risk of older adults: translating biomechanical results to the clinic. *J Electromyogr Kinesiol*. 2008;18:197–204. doi:10.1016/j.jelekin.2007.06.009
31. Crenshaw JR, Rosenblatt NJ, Hurt CP, Grabiner MD. The discriminant capabilities of stability measures, trunk kinematics, and step kinematics in classifying successful and failed compensatory stepping responses by young adults. *J Biomech*. 2012;45:129–133. doi:10.1016/j.jbiomech.2011.09.022
32. Kaufman KR, Wyatt MP, Sessoms PH, Grabiner MD. Task-specific fall prevention training is effective for warfighters with transtibial amputations. *Clin Orthop Relat Res*. 2014;472:3076–3084. doi:10.1007/s11999-014-3664-0
33. Owings TM, Pavol MJ, Grabiner MD. Mechanisms of failed recovery following postural perturbations on a motorized treadmill mimic those associated with an actual forward trip. *Clin Biomech (Bristol, Avon)*. 2001;16:813–819. doi:10.1016/S0268-0033(01)00077-8
34. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *N Engl J Med*. 1988;319:1701–1707. doi:10.1056/NEJM198812293192604
35. van Dieen JH, Pijnappels M, Bobbert MF. Age-related intrinsic limitations in preventing a trip and regaining balance after a trip. *Saf Sci*. 2005;43:437–453. doi:10.1016/j.ssci.2005.08.008
36. Pavol MJ, Owings TM, Foley KT, Grabiner MD. Mechanisms leading to a fall from an induced trip in healthy older adults. *J Gerontol A Biol Sci Med Sci*. 2001;56:M428–M437. doi:10.1093/gerona/56.7.M428
37. Grabiner MD, Crenshaw JR, Hurt CP, Rosenblatt NJ, Troy KL. Exercise-based fall prevention: can you be a bit more specific? *Exerc Sport Sci Rev*. 2014;42:161–168. doi:10.1249/JES.0000000000000023
38. Schoene D, Wu SM, Mikolaizak AS, et al. Discriminative ability and predictive validity of the timed up and go test in identifying older people who fall: systematic review and meta-analysis. *J Am Geriatr Soc*. 2013;61:202–208. doi:10.1111/jgs.12106
39. Brauer SG, Burns YR, Galley P. A prospective study of laboratory and clinical measures of postural stability to predict community-dwelling fallers. *J Gerontol A Biol Sci Med Sci*. 2000;55:M469–M476. doi:10.1093/gerona/55.8.M469
40. Sherrington C, Tiedemann A, Fairhall N, Close JC, Lord SR. Exercise to prevent falls in older adults: an updated meta-analysis and best practice recommendations. *N S W Public Health Bull*. 2011;22:78–83. doi:10.1071/NB10056