Sports Medicine and Health Science 7 (2025) 208–213

Contents lists available at ScienceDirect

Sports Medicine and Health Science

journal homepage: www.keaipublishing.com/smhs

Original Article

Combined effects of Tai-Chi gait with mediolateral ground support perturbation on dynamic balance control

Jacob Smith [a], Troilyn Jackson [a], Wei Liu [b], Jonathan Gelfond [c], Hao-Yuan Hsiao [a,*]

[a] University of Texas at Austin, Department of Kinesiology and Health Education, TX, USA
[b] University of Texas Health Science Center at San Antonio, Department of Physical Therapy, TX, USA
[c] University of Texas Health Science Center at San Antonio, School of Medicine, TX, USA

ARTICLE INFO

Keywords:
Tai-Chi
Gait
Dynamic stability
Perturbation
Balance
Aging

ABSTRACT

Tai-Chi (TC) is a broadly used exercise that appeared to decrease the risk of falls. However, biomechanical mechanisms underlying the reduced fall risks following TC exercise remain unclear and hinder the ability to optimize TC intervention to target specific balance deficit disorders. In addition, combining TC gait exercise with ground support perturbation may be a viable approach to further challenge balance control compared to TC gait alone. The purpose of this study was to compare dynamic stability and limb support force production during comfortable walking speed (CWS), TC gait, and TC gait with medial (MED) and lateral (LAT) ground support perturbations in older and younger adults. Ten older adults and ten younger adults performed CWS, TC gait, LAT, and MED. Conditions involving TC gait showed decreased margin of stability (MoS) (main effect of condition, $p < 0.01$) and increased vertical force impulse compared to CWS ($p < 0.01$). Medial ground support perturbation induced the smallest MoS among all conditions. Older adults showed increased MoS compared to younger adults ($p < 0.01$). These findings provided insight into how key balance control characteristics are modulated during TC exercise and indicate that combining ground support perturbation with TC may further challenge dynamic stability.

1. Introduction

Falls are a serious public health concern among older adults because they occur frequently and cause severe consequences. Approximately one third of older adults fall every year[1] and those who are hospitalized or live in a nursing home fall more often. Dysfunction resulting from fall-related injuries affects performance of daily activities such as bathing, self-care, and walking, and can thus adversely affect independence and quality of life. Consequently, preventing falls in older people has become an increasingly important task.

Aging-related changes in balance and gait associated with neuromusculoskeletal impairments have been consistently found to be among the most important risk factors for falls.[2] In addition, those who fall present greater impairments in neuromusculoskeletal factors than do older non-fallers.[3] From a biomechanical standpoint, maintaining balance requires the ability to control dynamic stability and generate sufficient support force against gravity.[4,5] Not surprisingly, deficits in dynamic stability regulation and limb support force production are key risk factors for falls.[6,7] Developing exercise and intervention approaches that improve dynamic stability control and limb support force production may reduce the risk of falls among older adults.

Tai-Chi (TC) is a traditional Chinese exercise derived from martial art that has gained increasing attention for preventing falls.[8] TC gait is one of the 24 forms of all-style TC and is the basic but most common leg motions in TC movements.[9] TC gait is a cyclic motion with both legs alternating between bow-leg posture and high swing while traveling forward (Brush left knee, twist and roll back, step forward, right palm forward strike; Brush right knee, twist and roll back, step forward, left palm forward strike). TC gait also has a periodic motion with temporal patterns similar to regular gait. In the past two decades, promising evidence suggests that TC provides multiple benefits that include increased postural stability, improved muscular strength, pain reduction for patients with arthritis, decreased stress and enhanced cardiovascular function.[10–14] TC demonstrated superior effectiveness in protecting against falls in older adults compared to other interventions including conventional physical therapy,[15] stretching and multimodal exercise,[16] and conventional lower extremity training.[17] In addition, group TC interventions for older adults

* Corresponding author. University of Texas at Austin, Department of Kinesiology and Health Education, TX, USA
E-mail address: hhsiao@austin.utexas.edu (H.-Y. Hsiao).

https://doi.org/10.1016/j.smhs.2024.07.002
Received 11 January 2024; Received in revised form 17 May 2024; Accepted 3 July 2024
Available online 9 July 2024

Abbreviations

TC	Tai-Chi
MED	Medial ground support perturbation
LAT	Lateral ground support perturbation
CWS	Comfortable walking speed
MoS	Margin of stability
ML MoS	Mediolateral margin of stability
CoM	Center of mass
XCoM	Extrapolated center of mass
VCoM	Center of mass velocity
BoS	Base of support
GRF	Ground reaction force
g	Gravity
l	Leg length
ASIS	Anterior superior iliac spine
ANOVA	Analysis of variance
m	Meters

may increase social support and therefore further increase health benefits.[18] Consequently, the U.S. Center for Disease Control and Prevention has recommended TC training as an optional evidence-based fall prevention intervention for older adults.[19]

Despite being a broadly used fall prevention exercise, previous randomized controlled trials showed inconsistent results in the effectiveness of TC on fall prevention among older adults.[8,20,21] This is, at least in part, because the direct balance control mechanisms that are involved during TC movements remain largely undetermined.[22] Such knowledge gap limits the ability to design specific TC movements for targeted deficits. As a result, previous clinical trials included multiple complex TC forms and the outcomes represent a net effect of various mixed types of movements. Identifying the biomechanical mechanisms by which TC movements can improve balance control in older adults will enhance the development of more effective TC exercise interventions.

During a fall, rapid reactions are commonly required to adjust posture for balance recovery. A recent study reported that treadmill-based reactive balance training resulted in better rapid balance responses compared to TC training alone,[23] reflecting a potential limitation for traditional TC exercise. This is likely because TC typically practices slow and mindful voluntary control of motion that does not target reactive movements. In contrast, studies that applied external perturbations such as using a movable ground support or cable systems to pull the body triggered rapid balance recovery reactions. Recent perturbation-based training has shown positive outcomes in older adults[24–26] and other clinical populations[27,28] likely because such rapid reactions are required to prevent a fall. Since balance regulation involves both voluntary and reactive movements, developing an approach that targets both voluntary and reactive aspects of balance control is likely to be more effective than exercises that focus on a single aspect alone. To date, the feasibility of combining TC gait with external perturbation exercises and their effects on dynamic stability and limb support remain unknown.

To address the aforementioned knowledge gaps, this study aimed to compare the dynamic stability and limb support force production during normal walking, TC gait, and TC with medial (MED) and lateral (LAT) ground support perturbations in younger and older adults. It was hypothesized that compared to regular walking, conditions involving TC will show decreased dynamic stability with increased limb support force in both younger and older adults. In addition, we hypothesized that by shifting the foot more medially, MED will induce the least margin of stability (MoS) amongst all conditions tested.

2. Materials and methods

2.1. Participants

Ten older adults and 11 younger adults participated in the study. Data from 1 younger adult was not analyzed due to missing markers. Data for the remaining 10 younger adults were included in the study. The inclusion criteria were: (1) Able to walk for at least 10 minutes(min) without an assistive device or assistance from another individual. (2) Have sufficient cognitive function to follow the instructions. Participants were excluded if they have a medical history that includes lower extremity orthopedic, neurological, vascular, or metabolic pathological conditions affecting gait.

2.2. Ethical approval

The study was approved by the Institutional Review Board of the University of Texas at Austin. All participants provided written informed consent to participate. Approval number: STUDY00001792.

2.3. Testing procedure

Prior to data collection, a TC instructor demonstrated TC gait to each participant. The participant practiced the movement until the instructor confirmed correctness of movement. Next, participants wore a safety harness connected to an overhead support beam. Comfortable walking speed and TC gait speed were determined by gradually increasing the treadmill speed until the subject reported comfortable speed attained. A familiarization period was provided for walking and TC gait until participants confirmed that familiarization has been achieved (Fig. 1). Next, each participant performed three tasks on a split-belt treadmill: comfortable speed walking (CWS), TC gait, and TC gait with treadmill medial (MED) and lateral (LAT) ground support perturbations. During the TC gait with perturbation, the treadmill translated (3 cm within 370 ms) medially or laterally during early single leg stance phase. The direction of the perturbation was pseudo-randomized to minimize participants' anticipation. Treadmill perturbations occurred during single limb stance phase of the gait cycle in the MED and LAT conditions. The time interval between each perturbation was at least 3 second (s) to allow recovery to regular TC gait.

2.4. Data recording

Reflective markers were placed on the forehead and bilaterally on the acromion process, lateral epicondyle of the humerus, distal end of the radius, anterior superior iliac spine (ASIS), posterior superior iliac spine, greater trochanter (hip), lateral epicondyle of the femur (knee), lateral malleolus (ankle), second metatarsal, and heel. An additional marker was placed on the treadmill platform to track the treadmill movement during perturbation trials. Body segment position data were recorded using a 10-camera motion capture system (Vicon-USA, Denver, CO) sampled at 120 Hz and then low-pass filtered at 6 Hz in the Visual3D software (C-Motion, Inc., Rockville, MD, USA). Ground reaction forces (GRF) were measured by an instrumented treadmill (M-gait, Motek, Netherland) sampled at 1 000 Hz and then low-pass filtered at 30 Hz in Visual3D. For CWS, a 30 s trial was recorded (~27 strides). For TC, a 2 min trial was recorded (~16 strides). For TC MED and LAT conditions, a 6 min trial was recorded (16 MED and 16 LAT steps).

2.5. Data analyses

Lateral margin of stability (MoS) was used to characterize dynamic stability (Fig. 2).[29] The extrapolated center of mass (XCoM) was calculated by.[30]

Fig. 1. Participants underwent a Tai-Chi (TC) familiarization period on a treadmill.

$$XCoM = CoM + VCoM \Big/ \sqrt{\frac{g}{l}} \quad (1)$$

where center of mass (CoM*)* and velocity of CoM (VCoM) were the lateral position and velocity of the center of mass (VCoM) relative to the walking surface, respectively. g was the gravity constant (9.81 $m \cdot s^{-2}$), and l was leg length, defined as the distance from the ASIS to the medial malleolus, multiplied by 1.34.[30] Lateral MoS was calculated by using

$$MoS = BoS - XCoM \quad (2)$$

where base of support (BoS) was the lateral boundary of the base of support defined by the second metatarsal marker of the stance limb. The minimal value of MoS during the single leg stance phase was used to determine dynamic stability. Positive MoS values indicated more stable (XCoM within BoS) and negative MoS values indicate less stable (XCoM outside BoS).[31] Limb support was characterized by calculating the time integral of the vertical GRF during single stance phase (i.e., vertical force impulse).[32] For CWS and TC conditions, Lateral MoS and vertical force impulse were calculated for each step and averaged across trials within each condition. Vertical force impulse was normalized to body weight. For perturbation conditions, only the perturbed steps were analyzed. Single limb stance phase was defined as the time between contralateral limb liftoff/toe-off to contralateral limb heel-strike. Heel strike and toe-off events were determined as the instant that vertical ground reaction force exceeded or dropped below 20 N,[33,34] respectively.

Since external balance perturbations may result in aborted steps, we additionally determined the proportion of aborted steps by calculating the ratio of the number of aborted steps over the total number of perturbed steps. The aborted steps were characterized by initial foot lift-off followed by an immediate compensatory step (rapid foot plant down identified by increases in vertical GRF) instead of entering a swing phase.[35] Lateral MoS and vertical force impulse data from the aborted steps were excluded from the final statistical analyses because the balance recovery effort transferred to the contralateral limb and not the perturbed limb.[36]

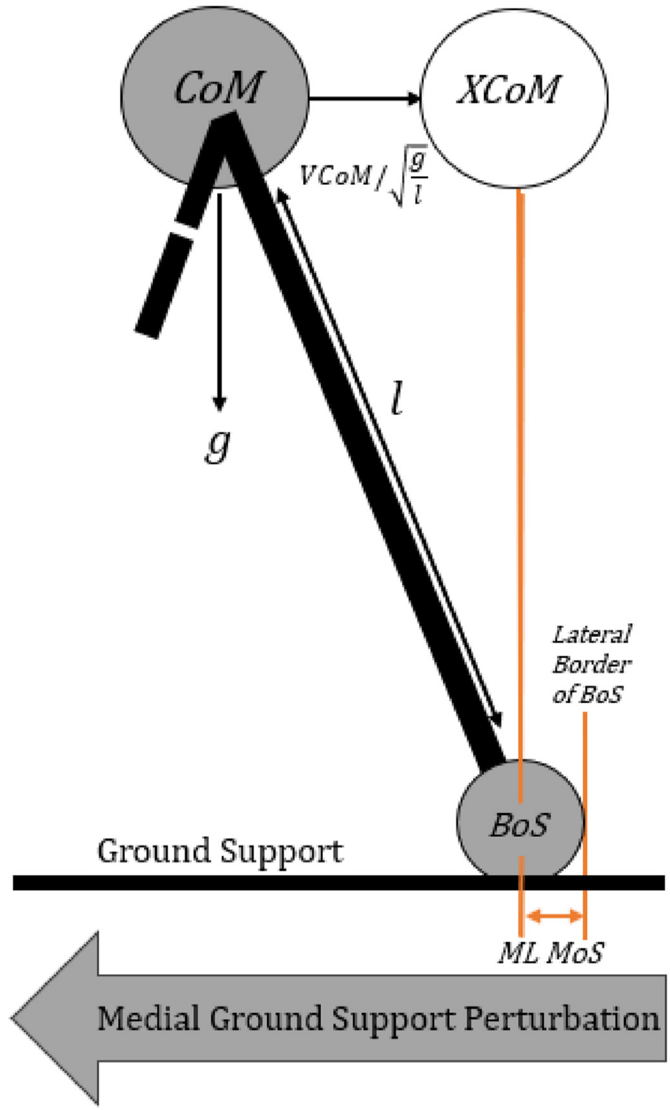

Fig. 2. The inverted pendulum model[51] illustrates the mediolateral margin of stability (ML MoS) in the frontal plane. ML MoS was calculated by the distance between the extrapolated center of mass position (XCoM*)* and the lateral border of base of support (BoS) which is defined by the second metatarsal marker of the stance limb. Center of mass velocity (VCoM), gravity (g), constant (9.81 $m \cdot s^{-2}$), leg length (l), defined as the distance from the anterior superior iliac spine marker to the medial malleolus, multiplied by 1.34, were used to calculate XCoM. An arrow illustrating the direction of the medial ground support perturbation during single limb stance is shown beneath the ground support.

2.6. Statistical analysis

Two-way (condition × age group) mixed model analysis of variance (ANOVA) was performed to analyze mediolateral MoS, vertical force impulse, and gait speed. If the interaction or main effect was significant, Bonferroni post-hoc test was performed for pairwise comparisons. All statistics were performed in SPSS (version 22.0, SPSS, Inc.) with a two-sided alpha level of 0.05.

3. Results

3.1. Demographics and gait speed

The younger group was 40% (4/10) female with the following means and standard deviations for baseline characteristics: age (27.8 ± 5.05) year, height (1.73 ± 0.11) m, weight (70.08 ± 14.57) kg, and the 10 older adults (5/10 female) had the following baseline characteristics: age (69.7 ± 5.35) year; 5 females; height (1.67 ± 0.06) m; weight (69.46 ± 10.5) kg. All participants completed the trials in all conditions with no falls occurred during the testing trials. During the perturbation conditions, aborted steps were observed in 10% (±21%) of the MED trials and 18% (±32%) of the LAT trials in younger adults. Older adults showed 8% (±11%) and 16% (±17%) aborted steps during MED and LAT, respectively. During CWS, the speed was (1.005 ± 0.06) $m \cdot s^{-1}$ for younger participants and (0.94 ± 0.048) $m \cdot s^{-1}$ for older participants. During TC conditions, the speed was (0.075 ± 0.005) $m \cdot s^{-1}$ for younger participants and (0.08 ± 0.005) $m \cdot s^{-1}$ for older participants. A 2-way (age × condition) ANOVA on walking speed was performed. A main effect of condition was detected ($F_{[1,18]} = 489.439$, $p < 0.001$). Pairwise comparisons revealed significant mean differences between CWS and TC gait speed in older adults (mean difference: CWS – TC = 0.957, $p < 0.001$) and younger adults (mean difference: CWS – TC = 0.860, $p < 0.001$). No interaction or main effect of age was detected.

3.2. Mediolateral margin of stability

For mediolateral MoS, main effects of condition ($F_{[3,30]} = 103.51$, $p < 0.01$) and age ($F_{[1,10]} = 4.605$, $p < 0.05$) were observed. Post Hoc analysis revealed that CWS had greater MoS compared to all other conditions ($p < 0.01$, between condition differences: CWS – TC = 0.036, CWS – LAT = 0.044, CWS – MED = 0.045 m) and MED has smaller MoS compared to all other conditions ($p < 0.01$) (Fig. 3). In addition, older adults showed increased MoS compared to younger adults ($p < 0.05$). No interaction was detected.

3.3. Vertical force impulse

For vertical force impulse, a main effect of condition was detected ($F_{[1,10]} = 146.548$, $p < 0.01$) (Fig. 4). CWS has smaller vertical force impulse compared to all other conditions ($p < 0.01$, between condition differences: CWS – TC = −3.705 N*S/BW, CWS – LAT = −17.913 N*S/BW, CWS – MED = −17.808 N*S/BW). LAT showed reduced force impulse compared to TC ($p < 0.01$) and MED ($p < 0.01$) conditions. No interaction between age group and conditions was detected.

4. Discussion and implications

The present study determined the effects of TC gait and TC gait combined with ground support perturbation on dynamic stability and limb support in younger and older adults. Results showed that compared to regular walking, all conditions that involved TC gait showed decreased MoS and increased vertical force impulse. In addition, MED induced the smallest MoS among all conditions. These findings indicate that combining treadmill surface perturbation with TC gait may be an effective and feasible approach to challenge lateral dynamic stability and limb support force production.

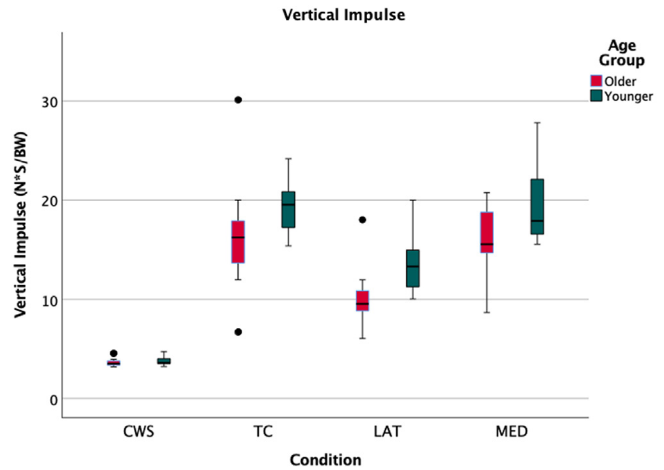

Fig. 4. Vertical force impulse for older and younger adults during comfortable walking speed (CWS), Tai-Chi (TC) gait, TC with lateral ground support perturbation (LAT), and TC with medial ground support perturbation (MED). Older adults are labeled red and younger adults are labeled green. Outliers are represented by the black circles above and below the whiskers of the clustered boxplot.

Compared to regular walking, all conditions involving TC gait showed decreased MoS, reflecting that dynamic stability was more challenged during TC gait. Because TC gait emphasizes body transfer from one leg to the other, individuals likely shifted their body closer to the base of support boundary compared to regular walking that does not focus on weight shifting. Our finding expanded the results from a recent study that reported decreased anterior-posterior MoS during TC gait[37] by showing that TC also challenged lateral stability compared to regular walking. In addition, conditions involving TC gait showed increased limb support compared to regular walking. This is likely due to the slower pace during TC gait that led to increased single leg stance duration. While walking at a slower speed, ground contract duration for each step is typically increased and thereby generates greater force impulse (the integral of force × contact duration).[42] Taken together, TC gait appeared to increase the demand for stance leg force production and lateral balance regulation. These results provide potential biomechanical mechanisms underlying the reduced fall risks following TC exercises.[38–40]

Our results showed that older adults generally demonstrated larger MoS across conditions compared to younger adults. A potential

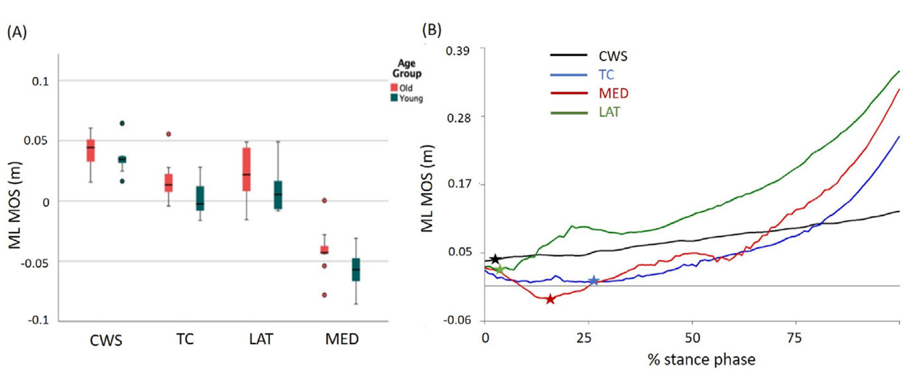

Fig. 3. Mediolateral margin of stability (ML MoS) across conditions measured in meters (m). (A) Comparisons of ML MoS in older and younger adults during Comfortable Walking Speed (CWS), Tai-Chi (TC) gait, TC with lateral ground support perturbation (LAT), and TC with medial ground support perturbation (MED). Older adults are labeled red and younger adults are labeled green. (B) Representative trials of ML MoS values during single leg stance phase across conditions. The black line represents the CWS condition, the blue line represents the TC condition, the red line represents the MED condition, and the green line represents the LAT condition. The star symbol on each line represents minimum ML MoS.

explanation could be that older adults adopted a relatively conservative strategy that prioritizes stability during locomotion. In contrast, younger adults may feel more confident shifting their body toward the base of support boundary. This observation is in agreement with previous findings that older adults adopted a more conservative strategy during obstacle crossing[41] and following perturbations[41,42] compared to young. Importantly, when TC was combined with medial perturbations, both groups demonstrated negative MoS. Thus, inducing medial ground support perturbation may be an effective approach to further challenge lateral dynamic stability for older adults who tend to use more conservative strategies during voluntary TC exercise. However, older adults did not show decreased force compared to younger adults. This is similar to previous findings where no differences in vertical impulse were found between younger and older adults when approaching raised surfaces[43] and during stair descent.[44] Older participants in the present study were relatively healthy and active. Thus, they may retain the force production ability closer to younger adults. Despite similar force production capacity, previous gait studies have reported that older and younger adults may use different strategies to produce vertical force during gait.[45–47] Future work that compares mechanisms of vertical impulse production during TC gait in older and younger adults may provide useful information.

To our knowledge, this is the first study to combine balance perturbation with TC gait. Our results demonstrated that combining TC with ground support perturbation appeared to be feasible and tolerable as only a low percentage of trials led to aborted steps. In addition, medial perturbation during single limb stance induced greater challenges in dynamic stability and limb support force production compared to lateral perturbation. This is likely because lateral shift of the support surface increased the distance between the stance foot and the CoM and participants reacted by putting down the swing foot to terminate the single stance duration earlier to regain stability.[48] It is important to note that while the results showed that MED could better challenge individuals' ability to maintain lateral stability during single leg stance, the ability to rapidly plant the swing leg down is also a useful strategy for balance recovery.[49] Thus, MED and LAT perturbations could be used to target different balance control mechanisms. Findings from this study could guide future research to develop new rehabilitation protocols that aim to improve balance ability by combining TC gait with ground support perturbations.

There are limitations to this study. First, only one perturbation intensity was tested. Different perturbation intensities (e.g. acceleration or displacement) could induce different levels of challenges in lateral stability and support force production. In addition, the number of aborted steps may be reduced by using perturbations with reduced intensity. Future research that explores the effects of perturbation intensity on postural reactions during TC gait may provide useful information for rehabilitation strategy design to target various functional levels in clinical populations. Another limitation is that as proof of concept, only one TC form was tested in this study. However, TC gait is a basic and most common leg motion in TC movements and therefore will likely be most relevant in understanding TC's effect on balance performance and postural control.[42] There are also other types of exercises such as fast pace or backward walking that requires less learning and may challenge different aspects of balance regulation. How TC gait affects different components of balance control compared to other exercises remains to be determined. Lastly, the inverted pendulum model used for MOS calculation assumed no changes in leg length. Although the calculated changes in leg length during the single stance duration in the present study (averaging 14.9 mm in CWS perturbations and 17.2 mm during TC perturbations) appeared to be within an acceptable range compared to previous gait research that applied the inverted pendulum model and reported leg length changes of 30 mm,[50] this may still affect the accuracy of estimated dynamic stability.

5. Conclusions

Compared to regular walking, TC gait induced greater demand in dynamic stability and limb support force generation. When combined with support surface medial perturbation, dynamic stability could be further challenged during TC gait. This information could guide future research to develop rehabilitation approaches that aim to improve balance ability in aging.

Ethical approval

The study was approved by the Institutional Review Board of the University of Texas at Austin and all participants provided written informed consent to participate. Approval number: STUDY00001792.

Data statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Funding

College of Education Small Grant Award at the University of Texas at Austin.

CRediT authorship contribution statement

Jacob Smith: Writing – review & editing, Writing – original draft, Formal analysis. **Troilyn Jackson:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Wei Liu:** Writing – review & editing, Writing – original draft, Data curation. **Jonathan Gelfond:** Writing – review & editing. **Hao-Yuan Hsiao:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Stevens JA, Mack KA, Paulozzi LJ, Ballesteros MF. Self-reported falls and fall-related injuries among persons aged>or=65 years–United States, 2006. *J Saf Res*. 2008; 39(3):345–349. https://doi.org/10.1016/j.jsr.2008.05.002.
2. Maki BE, Mcilroy WE. Control of compensatory stepping reactions: age-related impairment and the potential for remedial intervention. *Physiother Theory Pract*. 1999;15(2):69–90. https://doi.org/10.1080/095939899307784.
3. Campbell AJ, Borrie MJ, Spears GF. Risk factors for falls in a community-based prospective study of people 70 years and older. *J Gerontol*. 1989;44(4):M112–M117. https://doi.org/10.1093/geronj/44.4.m112.
4. Melzer I, Kurz I, Oddsson LI. A retrospective analysis of balance control parameters in elderly fallers and non-fallers. *Clin Biomech*. 2010;25(10):984–988. https://doi.org/10.1016/j.clinbiomech.2010.07.007.
5. Pai Y-C, Yang F, Wening JD, Pavol MJ. Mechanisms of limb collapse following a slip among young and older adults. *J Biomech*. 2006;39(12):2194–2204. https://doi.org/10.1016/j.jbiomech.2005.07.004.
6. Tajali S, Rouhani M, Mehravar M, Negahban H, Sadati E, Oskouei AE. Effects of external perturbations on anticipatory and compensatory postural adjustments in patients with multiple sclerosis and a fall history. *Int J MS Care*. 2018;20(4):164–172. https://doi.org/10.7224/1537-2073.2016-098.
7. 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(2):e013661. https://doi.org/10.1136/bmjopen-2016-013661.
8. Lan C, Chen SY, Lai JS, Wong MK. The effect of Tai Chi on cardiorespiratory function in patients with coronary artery bypass surgery. *Med Sci Sports Exerc*. 1999;31(5): 634–638. https://doi.org/10.1097/00005768-199905000-00002.
9. Yang F, Liu W. Biomechanical mechanism of Tai-Chi gait for preventing falls: a pilot study. *J Biomech*. 2020;105:109769. https://doi.org/10.1016/j.jbiomech.2020.109769.

10. Palumbo MV, Wu G, Shaner-McRae H, Rambur B, McIntosh B. Tai Chi for older nurses: a workplace wellness pilot study. *Appl Nurs Res*. 2012;25(1):54–59. https://doi.org/10.1016/j.apnr.2010.01.002.
11. Wolf SL, Barnhart HX, Kutner NG, McNeely E, Coogler C, Xu T. Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training. Atlanta FICSIT group. Frailty and injuries: Cooperative studies of intervention Techniques. *J Am Geriatr Soc*. 1996;44(5):489–497. https://doi.org/10.1111/j.1532-5415.1996.tb01432.x.
12. Wu G, Keyes L, Callas P, Ren X, Bookchin B. Comparison of telecommunication, community, and home-based Tai Chi exercise programs on compliance and effectiveness in elders at risk for falls. *Arch Phys Med Rehabil*. 2010;91(6):849–856. https://doi.org/10.1016/j.apmr.2010.01.024.
13. Wu G, Zhao F, Zhou X, Wei L. Improvement of isokinetic knee extensor strength and reduction of postural sway in the elderly from long-term Tai Chi exercise. *Arch Phys Med Rehabil*. 2002;83(10):1364–1369. https://doi.org/10.1016/j.apmr.2010.01.024.
14. Tousignant M, Corriveau H, Roy PM, Desrosiers J, Dubuc N, Hébert R. Efficacy of supervised Tai Chi exercises versus conventional physical therapy exercises in fall prevention for frail older adults: a randomized controlled trial. *Disabil Rehabil*. 2013;35(17):1429–1435. https://doi.org/10.3109/09638288.2012.737084.
15. Li F, Harmer P, Eckstrom E, Fitzgerald K, Chou LS, Liu Y. Effectiveness of Tai Ji Quan vs multimodal and stretching exercise interventions for reducing injurious falls in older adults at high risk of falling: follow-up analysis of a randomized clinical trial. *JAMA Netw Open*. 2019;2(2):e188280. https://doi.org/10.1001/jamanetworkopen.2018.8280.
16. Hwang HF, Chen SJ, Lee-Hsieh J, Chien DK, Chen CY, Lin MR. Effects of home-based Tai Chi and lower extremity training and self-practice on falls and Functional uutcomes in older fallers from the emergency department-A randomized controlled trial. *J Am Geriatr Soc*. 2016;64(3):518–525. https://doi.org/10.1111/jgs.13952.
17. Koren Y, Leveille S, You T. Tai Chi interventions promoting social support and interaction among older adults: a systematic review. *Res Gerontol Nurs*. 2021;14(3):126–137. https://doi.org/10.3928/19404921-20210325-02.
18. Noonan RK, Stevens JA, Baldwin G. The public health approach to older adult fall prevention: Comments from the U.S. centers for disease control and prevention. *Open Longev Sci*. 2011;5:26–31.
19. Logghe IH, Verhagen AP, Rademaker AC, et al. The effects of Tai Chi on fall prevention, fear of falling and balance in older people: a meta-analysis. *Prev Med*. 2010;51(3-4):222–227. https://doi.org/10.1016/j.ypmed.2010.06.003.
20. Woo J, Hong A, Lau E, Lynn H. A randomised controlled trial of Tai Chi and resistance exercise on bone health, muscle strength and balance in community-living elderly people. *Age Ageing*. 2007;36(3):262–268. https://doi.org/10.1093/ageing/afm005.
21. Hackney ME, Wolf SL. Impact of Tai Chi Chu'an practice on balance and mobility in older adults: an integrative review of 20 years of research. *J Geriatr Phys Ther*. 2014;37(3):127–135. https://doi.org/10.1519/JPT.0b013e3182abe784.
22. Aviles J, Allin LJ, Alexander NB, Van Mullekom J, Nussbaum MA, Madigan ML. 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. *J Gerontol A Biol Sci Med Sci*. 2019;74(9):1497–1503. https://doi.org/10.1093/gerona/glz018.
23. 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(12):2294–2303. https://doi.org/10.1111/ggi.13082.
24. 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(5):700–709. https://doi.org/10.2522/ptj.20140090.
25. Rogers MW, Creath RA, Gray V, et al. Comparison of lateral perturbation-induced step training and hip muscle strengthening exercise on balance and falls in community-dwelling older adults: a blinded randomized controlled trial. *J Gerontol A Biol Sci Med Sci*. 2021;76(9):e194–e202. https://doi.org/10.1093/gerona/glab017.
26. Esmaeili V, Juneau A, Dyer JO, et al. Intense and unpredictable perturbations during gait training improve dynamic balance abilities in chronic hemiparetic individuals: a randomized controlled pilot trial. *J NeuroEng Rehabil*. 2020;17(1):79. https://doi.org/10.1186/s12984-020-00707-0.
27. Martelli D, Luo L, Kang J, Kang UJ, Fahn S, Agrawal SK. Adaptation of stability during perturbed walking in Parkinson's Disease. *Sci Rep*. 2017;7(1):17875. https://doi.org/10.1038/s41598-017-18075-6.
28. McAndrew Young PM, Wilken JM, Dingwell JB. Dynamic margins of stability during human walking in destabilizing environments. *J Biomech*. 2012;45(6):1053–1059. https://doi.org/10.1016/j.jbiomech.2011.12.027.
29. Hof AL, Gazendam MG, Sinke WE. The condition for dynamic stability. *J Biomech*. 2005;38(1):1–8. https://doi.org/10.1016/j.jbiomech.2004.03.025.
30. Bruijn SM, Meijer OG, Beek PJ, van Dieën JH. Assessing the stability of human locomotion: a review of current measures. *J R Soc Interface*. 2013;10(83):20120999. https://doi.org/10.1098/rsif.2012.0999.
31. Kharb A, Saini V, Jain YK, Dhiman S. A review of gait cycle and its parameters. *Int J Comput Eng Manag*. 2011;13:78–83.
32. Salot P, Patel P, Bhatt T. Reactive balance in individuals with chronic stroke: biomechanical factors related to perturbation-induced backward falling. *Phys Ther*. 2016;96(3):338–347. https://doi.org/10.2522/ptj.20150197.
33. Breine B, Malcolm P, Galle S, Fiers P, Frederick EC, De Clercq D. Running speed-induced changes in foot contact pattern influence impact loading rate. *Eur J Sport Sci*. 2019;19(6):774–783. https://doi.org/10.1080/17461391.2018.1541256.
34. van Drongelen S, Wesseling M, Holder J, Meurer A, Stief F. Knee load distribution in hip osteoarthritis patients after total hip replacement. *Front Bioeng Biotechnol*. 2020;8:578030. https://doi.org/10.3389/fbioe.2020.578030.
35. Forner Cordero A, Koopman HF, van der Helm FC. Multiple-step strategies to recover from stumbling perturbations. *Gait Posture*. 2003;18(1):47–59. https://doi.org/10.1016/s0966-6362(02)00160-1.
36. Zhong D, Li J, Yang H, et al. Tai Chi for Essential Hypertension: a systematic review of randomized controlled trials. *Curr Hypertens Rep*. 2020;22(3):25. https://doi.org/10.1007/s11906-020-1031-y.
37. Penn IW, Sung WH, Lin CH, Chuang E, Chuang TY, Lin PH. Effects of individualized Tai-Chi on balance and lower-limb strength in older adults. *BMC Geriatr*. 2019;19(1):235. https://doi.org/10.1186/s12877-019-1250-8.
38. Wu MT, Tang PF, Goh JOS, et al. Task-switching performance improvements after Tai Chi Chuan training are associated with greater prefrontal activation in older adults. *Front Aging Neurosci*. 2018;10:280. https://doi.org/10.3389/fnagi.2018.00280.
39. Zhong D, Xiao Q, Xiao X, et al. Tai Chi for improving balance and reducing falls: an overview of 14 systematic reviews. *Ann Phys Rehabil Med*. 2020;63(6):505–517. https://doi.org/10.1016/j.rehab.2019.12.008.
40. Woollacott MH, Tang PF. Balance control during walking in the older adult: research and its implications. *Phys Ther*. 1997;77(6):646–660. https://doi.org/10.1093/ptj/77.6.646.
41. Luchies CW, Alexander NB, Schultz AB, Ashton-Miller J. Stepping responses of young and old adults to postural disturbances: kinematics. *J Am Geriatr Soc*. 1994;42(5):506–512. https://doi.org/10.1111/j.1532-5415.1994.tb04972.x.
42. Matjačić Z, Zadravec M, Olenšek A. Influence of treadmill speed and perturbation Intensity on selection of balancing strategies during slow walking perturbed in the Frontal Plane. *Appl Bionics Biomech*. 2019;2019:1046459. https://doi.org/10.1155/2019/1046459.
43. Begg RK, Sparrow WA. Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls. *J Gerontol A Biol Sci Med Sci*. 2000;55(3):M147–M154. https://doi.org/10.1093/gerona/55.3.m147.
44. Saywell N, Taylor D, Boocock M. During step descent, older adults exhibit decreased knee range of motion and increased vastus lateralis muscle activity. *Gait Posture*. 2012;36(3):490–494. https://doi.org/10.1016/j.gaitpost.2012.05.007.
45. Foroughi F, Prible D, Hsiao HY. Age-associated changes in lower limb weight-bearing strategy during walking. *Gait Posture*. 2024;107:162–168. https://doi.org/10.1016/j.gaitpost.2023.10.007.
46. Chung MJ, Wang MJ. The change of gait parameters during walking at different percentage of preferred walking speed for healthy adults aged 20-60 years. *Gait Posture*. 2010;31(1):131–135. https://doi.org/10.1016/j.gaitpost.2009.09.013.
47. Toda H, Nagano A, Luo Z. Age and gender differences in the control of vertical ground reaction force by the hip, knee and ankle joints. *J Phys Ther Sci*. 2015;27(6):1833–1838. https://doi.org/10.1589/jpts.27.1833.
48. Wu G, Liu W, Hitt J, Millon D. Spatial, temporal and muscle action patterns of Tai Chi gait. *J Electromyogr Kinesiol*. 2004;14(3):343–354. https://doi.org/10.1016/j.jelekin.2003.09.002.
49. Rogers MW, Mille ML. Lateral stability and falls in older people. *Exerc Sport Sci Rev*. 2003;31(4):182–187. https://doi.org/10.1097/00003677-200310000-00005.
50. Saini M, Kerrigan DC, Thirunarayan MA, Duff-Raffaele M. The vertical displacement of the center of mass during walking: a comparison of four measurement methods. *J Biomech Eng*. 1998;120(1):133–139. https://doi.org/10.1115/1.2834293.
51. Watson F, Fino PC, Thornton M, Heracleous C, Loureiro R, Leong J. Use of the margin of stability to quantify stability in pathologic gait – a qualitative systematic review. *BMC Musculoskelet Disord*. 2021;22(1):597. https://doi.org/10.1186/s12891-021-04466-4.