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Perturbation exercises during treadmill walking improve pelvic and trunk motion in older adults—A randomized control trial

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ABSTRACT

Background: Most falls among older adults occur while walking. Pelvic and trunk motions are required to maintain stability during walking. We aimed to explore whether training that incorporates unexpected loss of balance during walking that evokes balance recovery reactions will improve pelvic, thorax, and trunk kinematics at different walking speeds.

Methods: Fifty-three community-dwelling older adults (age 80.1 ± 5.6 years) were randomly allocated to an intervention group ($n = 27$) or a control group ($n = 26$). Both groups received 24 training sessions over 3 months. The intervention group received unexpected perturbation of balance exercises during treadmill walking, while the control group performed treadmill walking only. The primary outcome measures were the pelvic, thorax, and trunk motion. The secondary outcome measures were stride times, length, and width.

Results: Compared to control, participation in the intervention program led to improvement in pelvic and trunk transverse rotations especially at participants' preferred walking speed. No improvement where found in pelvic list while thorax transverse rotation improved in both groups.

Conclusions: Pelvic and trunk transverse motion, parameters previously reported to deteriorate during aging, associated with gait stability and a risk factor for falls, can be improved by gait training that includes unexpected loss of balance.

1. Introduction

One of the major problems associated with aging is an increased susceptibility to falling (Peel, 2011). Falling is the sixth most common cause of death in older adults varying from 0.3 falls a year per older adult living in the community to 3 falls for high-risk older adults (Rubenstein, 2006), and may result in acute injuries (Centers for Disease Control & Prevention, 2017). Minimizing falls is critical for maintaining function, and reduce disability in older adults. Many falls in older adults occur during walking (Robinovitch, Feldman, & Yang, 2013), and inability to recover from unexpected loss of balance during walking i.e., slips and trips (Luukinen et al., 2000), transitions from static to dynamic activities (Lord, Ward, Williams, & Ansety, 1993), and instable gait (Verghese, Holtzer, Lipton, & Wang, 2009; Weiss, Brozgol, & Dorfman, 2013; Toebes, Hoozemans, Furrer, Dekker, & van Dieën, 2012). Older adults show lower gait speed, shorter and wider strides, higher stride frequency, low hip extension torque during push-off (Judge et al., 1996), high stride variability (Hausdorff, Rios, & Edelberg, 2001), and declines in pelvic and trunk motion (Gimmon et al., 2015).

Older adults had differences in gait characteristics compared with younger adults (Gimmon et al., 2015) and with older adults who reported a recent fall (Barak, Wagenaar, & Holt, 2006). Recently, we observed that these changes in walking patterns in the older adults coincided with an increased stride frequency, a smaller stride length, decreased pelvic rotation, and reduced counter rotation in the thorax, resulting in decreased trunk rotation (Gimmon et al., 2015). Pelvic and trunk rotation are required for gait stability (Lamoth, Beek, & Meijer, 2002). More specifically, pelvic transverse rotation contribute to step length by reducing the need for a large hip flexion during walking (i.e., pelvic step), and reduces the movement of COM (Liang et al., 2014). Pelvic transverse rotation as well as pelvic list rotation are required for the control of the displacement of the center of mass (COM) for efficient energy expenditure (Lin, Gfoehler, & Pandy, 2014). Moreover, the momentum of pelvic transverse rotation and the trunk counter rotation, resulting in a smoother and more stable gait (Stokes, Andersson, &

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Forssberg, 1989). Insufficient trunk stability found to be associated with an increased risk of falls (Menz, Lord, & Fitzpatrick, 2003). Consequently, there is a need for developing effective balance exercises that can improve balance recovery responses as well as gait stability in older adults (i.e., improved altered pelvic and trunk rotations).

Balance exercises that include unexpected loss of balance during walking target those skills. These exercises facilitate explicitly the automatic balance responses such as cross over and side step stepping that require large functional pelvic and trunk motion. This may improve both gait stability and the ability to respond effectively to a loss of balance when fall is initiated pelvic and trunk motion. Information about how to improve functional pelvic and trunk motion during walking as well as the potential benefits of perturbation gait training to improve these parameters during walking have been minimally investigated.

Several studies trained balance recovery responses by performing perturbation exercises (Pai & Bhatt, 2007; Yang, Bhatt, & Pai, 2013; Kurz et al., 2016; Melzer & Oddsson, 2013; Mansfield, Peters, Liu, & Maki, 2010; Shimada, Obuchi, Furuna, & Suzuki, 2004). Trial-and error based workout led to adaptive improvements in balance recovery strategies (Pai & Bhatt, 2007), and generalization to “real life situations”, i.e., reduction in over 40% of laboratory-induced falls among older adults and 50% reduction in annual risk of falls (Pai, Bhatt, Yang, & Wang, 2014). Fall prevention programs are usually directed towards high-risk populations although age-related deterioration of balance function that leads to an increased risk of falling affects all older adults. Therefore, a better way to decrease the number of fall-related injuries, is to direct preventive efforts towards older adults who have not yet fallen. By improving the age related decline in gait stability (i.e., improved altered pelvic and trunk movements) and the ability to respond effectively to a loss of balance we may reduce the risk for fall. It is still unclear, however, whether this type of training impacted dynamic gait parameters, especially in respect to pelvic and trunk motion.

Principles of physical training and exercise include: awareness, continuity, motivation, overload, periodicity, progression and specificity. A successful balance and gait training must live by these rules otherwise, a training effect should not be expected. To be functionally useful, improving balance recovery responses and pelvic and trunk rotations during gait should preferably be designed into training intervention that closely mimic real life walking and losses of balance. This provides a specific challenge to the successful performance of functional tasks and may improve functional pelvic and trunk motion.

In the current study we examine whether perturbation training focused on evoking automatic balance recovery strategies during gait are able to improve pelvic and trunk motion that require for effective stepping responses during walking. Specifically, we targeted well-defined aspects of gait characteristics: (Peel, 2011) pelvis transverse rotation, (Rubenstein, 2006) pelvis list rotation, (Centers for Disease Control & Prevention, 2017) thorax transverse rotation, and (Robinovitch et al., 2013) trunk transverse rotation. We chose these outcome measures because previous studies demonstrated impairments in these specific characteristics of gait in older people (Gimmon et al., 2015) and older adults with a history of falls (Menz et al., 2003). Considering that automatic stepping responses during gait, especially cross-over stepping and lateral stepping responses, require ability to perform pelvic and trunk rotations, we hypothesize that older adults will significantly improve functional pelvic and trunk rotations during walking by participating in a treadmill gait training program that incorporates unexpected loss of balance.

2. Methods

This is an additional analysis of a previously reported RCT, where we found that voluntary stepping and postural stability was improved by participating in perturbation training (Kurz et al., 2016). Fifty–three older adults from two protected housing institutes were recruited. The eligibility criteria were: 70 years or older; independent walkers; score higher than 24 in Mini-Mental examination; no severe focal muscle weakness; no blindness; no neurological disorders; no metastatic cancer. Out of 72 seniors who were assessed for eligibility, 19 were excluded. All subjects provided a medical waiver signed by their primary care physician clearing them to participate in moderate physical exercise. The study was approved by the Helsinki Committee of Barzilai University Medical Center, Ashkelon, Israel (ClinicalTrials.gov Registration number #NCT01439451).

2.1. *Study design*

After signing an informed consent statement the subjects were randomized to two sites (27 and 26 subjects, respectively). In the first site, 14 subjects were randomly allocated to the intervention group and 13 to the control group. In the second site 13 subjects were randomly allocated to the intervention group and 13 to the control group using computer random allocation software (Random allocation software version 1.1, Isfahan Iran).

2.2. *Perturbation training programs*

Both intervention and control group subjects received a treadmill gait training program, with and without perturbations, respectively. All patients were treated two times per week for a period of 24 weeks. A mechatronic device that provides unexpected horizontal anterior-posterior and medio-lateral translations during treadmill walking was used (Shapiro & Melzer, 2010). Subjects in both groups were instructed to walk on a treadmill, at their own preferred walking speed with their hands free to swing. They wore a loose safety harness that allowed the subject to walk and to execute balance recovery reactions, but could arrest the fall if needed (Kurz et al., 2016; Shapiro & Melzer, 2010). The treadmill speed was increased until the subject said “It's too fast” and then treadmill speed decreased until the subject said “It’s too slow”. The midpoint of their self-reported speed was their “preferred treadmill speed”. While the control group subjects walked with no perturbation the intervention group received unannounced anterior, posterior, right, or left perturbations during walking. The therapist instructed the subjects to walk as naturally as possible. The perturbations were given in random order at 24 progressively more challenging training levels of difficulty with respect to the platform’s displacement, velocity, and acceleration of perturbation. Each session lasted 20 min, included 3 min warm-up treadmill walking, 14 min of perturbations gait training and 3 min of cool down walking. During each session, the listed platform translation unannounced perturbations were delivered in an unpredictable randomized sequence. Perturbations occurred randomly in all phases of gait cycle in order to increase the ecological validity. The perturbation was delivered after 20–30 s approximately. The level of perturbation was adjusted to match each subject’s ability and to be continuously challenging (details of the training program were published previously (Kurz et al., 2016)). The therapists involved in performing the intervention were not involved in conducting the baseline or the post-testing assessments.

The 24 training sessions. Each session lasted 20 min, included 3 min warm-up treadmill walking, 14 min of perturbations during comfortable treadmill walking, given in random direction (right, left, forward and backwards), and 3 min of cool down walking. The perturbation training program had 24 levels of difficulty with increasing levels of perturbations (i.e., increased displacement, velocity and accelerations of the horizontal translations). During each session, the listed platform translation unannounced perturbations were delivered in an unpredictable randomized sequence, in the directions indicated (forward, backward, left, and right). Perturbations for the treadmill walking were occur randomly (i.e., in all phases of gait cycle) in order to increase the ecological validity. The perturbation was delivered after 20–30 s approximately every 20 strides and was triggered randomly.

2.3. Gait kinematics assessments

During the baseline and post-test assessments, the subjects were instructed to walk on a treadmill wearing a loose safety harness, with their hands free to swing. They walked seven minutes, which included about two minutes for familiarization with the treadmill defining their own preferred walking speed and five minutes for data collection. The instructions were: "Walk as naturally as possible". During the five minutes for data collection, the treadmill's speed was systematically increased from 1.1 miles per hour (mph) to 1.9 mph in steps of 0.2 mph. Each treadmill speed was maintained for 40 s. The data was collected after about 10 s of adaptation (i.e., 30 s for motion data collection). In case the subject felt unsafe during one of the walking speeds the treadmill speed was then decreased to a lower walking speed, and the data for the unsafe walking speed were not included in the data analysis.

2.4. Measured and calculated parameters

The APAS 3D Analysis System (Ariel Dynamics Inc., CA, USA) was used to collect three-dimensional kinematic data. Two video cameras were placed approximately seven meters distant, at an angle of 45° in front of the treadmill. Motion was detected from eight reflective markers that were attached to the radial styloid process, the shoulder acromion process, the Anterior Superior Iliac Spines (ASIS), and the anterior aspect of ankle joints. The marker locations were sampled simultaneously at a frequency of 60 Hz, then transformed and smoothed using low-pass filter (Butterworth second-order forward and backward passes) with a cut-off frequency of 5 Hz. The APAS was shown to be valid and reliable, with a system mean point estimate error of less than 3.5 mm, 1.4 mm mean linear error, and 0.26° mean angular error (Klein & Dehaven, 1995).

Gait kinematics parameters were calculated using our own code written in Matlab (Math Works Inc., Cambridge, MA, USA). The gait cycle (stride time) was defined from toe-off to toe-off, enabling us to calculate the stride time, length, and width (details in reference (Gimmon et al., 2015)). Pelvic and thorax transverse rotations were detected through the 2 ASIS and the 2 acromion processes markers' movements, with respect to the frontal refference vector. After computing the pelvic and thorax angle in the transverse plane at each stride, the pelvic and thorax tROM were calculated using peak-to-peak angle during each gait cycle. Trunk rotation tROM was obtained by subtraction of the adjusted pelvic and thorax angles. The values presented are group average values ± SD of about 60 steps for each walking speed.

2.5. Sample size

The size estimation was based on a previous study (Gimmon et al., 2015), where the pelvic transverse tROM and pelvic list tROM in velocity of 1.3 m/s were 9.9° and 5.5°, respectively, for healthy young adults, 6.0° and 3.1°, respectively, for the older adults with SD of 4.0 and 2.3, respectively. Using the above numbers at a significance level of 0.05 and 80% power, a minimum of 17 and 8 subjects, respectively, in each group was required. Two-sided estimation was performed. Attrition rates of 25–35% have been reported in different populations of elderly individuals (McMurdo, Millar, & Daly, 2000). Thus, to account for the expected attrition rate a sample size of 23 is needed (17 × 1.35 = 23).

2.6. Statistical analysis

For statistical calculations PASW Statistics version 18.0 was used (Somers, NY, USA). Baseline characteristics were compared using Independent t-test and Mann-Whitney U test for continuous and ordinal variables, respectively. Descriptive data analysis and tests for the assumptions of normality (Shapiro-Wilk statistic) were followed by 2 × 2 Repeated Measure ANOVA (2 groups, 2 tests) for repeated measures with an alpha level of 0.05 for the subset of study participants who provided all data at baseline and after three months (i.e., 21 of the experimental and 19 of the control group subjects) was used to evaluate the effect of perturbation training on the average value of the pelvic and thorax motion at the "preferred walking speed". In addition 2 × 2 × 5 General Linear Model for repeated measures was performed. The independent variables were group (intervention vs. control) and time (baseline and post-testing) for five different walking speeds. The dependent variables were: pelvic transverse rotation, pelvic list rotation, and trunk and thorax rotation.

For each outcome, the Effect Size (ES) of Hedge's g and the 95% confidence interval (CI) were calculated. The ES of g was calculated by taking the difference between the means of both groups divided by the average population standard deviation (SD). To estimate the SD for g, baseline estimate SDs of both groups were pooled. The following guidelines were used when interpreting correlation magnitudes: 0.0–0.2 was considered small, 0.2–0.5 was considered moderate, and 0.5–0.8 was considered large (Hedges & Olkin, 1985).

3. Results

Group characteristics at base line showed no difference between groups other than age (Table 1). Six subjects dropped out during the training period in the experimental group and seven in the reference group.

3.1. Walking at the preferred walking speed

Table 2 shows a significant group-by-time increase in pelvic and trunk transverse tROM with large effect size with benefit to the intervention compared with the reference group ($p = 0.009$, [ES] = 0.5; $p = 0.017$, [ES] = 0.75, respectively). It should be noted that both groups significantly improved the thorax tROM after training, however no improvement was found in pelvic list rotation.

3.2. Walking at various walking speeds

Table 3 shows that the perturbation training resulted in a significant group-by-time increase in pelvic transverse tROM with a large effect size at 1.3 and 1.5 mph with benefit to the intervention group ($p = 0.027$, [ES] = 0.9; $p = 0.042$, [ES] = 0.9, respectively). There was also a trend towards a group-by-time increase in pelvic transverse tROM at 1.1 mph walking speed ($p = 0.055$, [ES] = 0.8). For pelvic list rotation, no significant group-by-time interaction effect was found for pelvic list at all gait speeds. The perturbation training resulted in a significant group-by-time improvement in thorax transverse tROM at

Table 1

Baseline characteristics of the intervention and reference group subjects and gait characteristics during walking in their preferred treadmill walking speed. Descriptive statistics and group comparisons. Values are means ± SD.

Variable	Intervention Group	Reference Group	p-value
Age (year)	78.2 ± 5.6	81.4 ± 4.3	0.05
% Female	62%	79%	0.25
Number of fallers (%)	11(37.9%)	11(39.3%)	0.92
Stride time (sec)	1.12 ± 0.1	1.18 ± 0.1	0.24
Stride length (cm)	0.68 ± 0.1	0.71 ± 0.1	0.57
Step width (cm)	18.4 ± 3.7	18.1 ± 2.9	0.64
Pelvic transverse tROM (°)	6.0 ± 3.0	5.5 ± 2.0	0.24
Thorax transverse tROM (°)	7.0 ± 3.3	6.9 ± 1.9	0.35
Pelvic list tROM (°)	3.7 ± 1.5	2.8 ± 1.1	0.04
Trunk transverse tROM (°)	13.1 ± 5.9	12.5 ± 3.0	0.68

Note: p-value compares baselines means in the two groups and, unless otherwise indicated, is based on t-test or chi-square.
cm = centimeters; sec = s; % = percent; tROM = total Range of Motion; (°) = °.

Table 2
Pelvic and trunk rotations in the subjects' preferred treadmill walking speed (mean ± SD).

Gait variables	Group	Baseline	post-test	ANOVA (Baseline to post-test) T	ANOVA (Baseline to post-test) T × G
Pelvic transverse rotation tROM (°)	Intervention	6.05 ± 3.0	7.98 ± 3.8	F = 1.96;	F = 7.7;
	Reference	5.50 ± 1.9	4.86 ± 1.2	*p* = 0.173	***p* = 0.009**
Pelvic list tROM (°)	Intervention	3.74 ± 1.5	3.67 ± 1.4	F = 1.9;	F = 1.0;
	Reference	2.81 ± 1.1	2.31 ± 1.0	*p* = 0.179	*p* = 0.319
Thorax transverse Rotation tROM (°)	Intervention	7.04 ± 3.2	8.94 ± 3.8	F = 9.9;	F = 2.7;
	Reference	6.96 ± 1.9	7.55 ± 2.6	***p* = 0.004**	*p* = 0.109
Trunk transverse Rotation tROM (°)	Intervention	13.1 ± 5.9	16.9 ± 6.8	F = 6.1;	F = 6.4;
	Reference	12.5 ± 3.0	12.4 ± 2.6	*p* = 0.02	***p* = 0.017**

Note: Comparison of baseline and post-intervention between the two groups based on repeated measures ANOVA (Test × Group).
Abbreviations: G = group; T = time; cm = centimeters, sec = s, % = percent; tROM = total Range of Motion; (°) = °; mph = miles per seconds; tROM = total Range of Motion; (°) = °

the highest walking speeds (1.5, 1.7, and 1.9 mph) with benefit to the intervention group ($p = 0.011$, [ES] = 0.90, $p = 0.030$, [ES] = 0.65; $p = 0.006$, [ES] = 0.8, respectively) (Table 3). Both groups significantly improved their thorax transverse rotation range of motion at 1.1 and 1.3 mph. A significant group-by-time increase in trunk transverse rotation with benefit to the intervention group was seen at three different gait speeds, i.e., 1.3 mph, 1.5 mph, and 1.9 mph ($p = 0.050$, [ES] = 0.89; $p = 0.017$, [ES] = 1.125; $p = 0.034$, [ES] = 1.06, respectively). In addition we found trends towards group-by-time significance for 1.1 mph and 1.7 mph ($p = 0.088$, [ES] = 0.91;

Table 3
Pelvic and trunk rotations at different treadmill walking speeds that systematically increased every 40 s from 1.1 miles per hour (mph) to 1.9 mph in steps of 0.2 mph (mean ± SD), group comparisons.

Gait variables	Group	Baseline	post-test	ANOVA (Baseline to post-test) T	ANOVA (Baseline to post-test) T × G
Pelvic transverse rotation tROM (°)					
1.1 mph	Intervention	5.24 ± 1.72	7.13 ± 3.90	F = 1.2;	F = 4.0;
	Reference	5.62 ± 2.14	5.07 ± 1.24	*p* = 0.283	*p* = 0.055
1.3 mph	Intervention	6.03 ± 2.87	8.24 ± 4.34	F = 2.3;	F = 5.3;
	Reference	5.48 ± 2.04	5.04 ± 1.33	*p* = 0.133	*p* = **0.027**
1.5 mph	Intervention	6.06 ± 2.33	8.35 ± 4.80	F = 3.1;	F = 4.5;
	Reference	5.37 ± 1.92	5.16 ± 1.23	*p* = 0.087	*p* = **0.042**
1.7 mph	Intervention	6.37 ± 3.87	8.74 ± 5.28	F = 1;	F = 1.8;
	Reference	5.34 ± 1.89	5.14 ± 1.05	*p* = 0.323	*p* = 0.188
1.9 mph	Intervention	6.68 ± 3.08	8.84 ± 4.21	F = 0.3;	F = 1.5;
	Reference	5.80 ± 2.24	5.35 ± 1.23	*p* = 0.587	*p* = 0.230
Pelvic list tROM (°)					
1.1 mph	Intervention	3.26 ± 1.21	2.97 ± 1.53	F = 3.0;	F = 0.6;
	Reference	3.14 ± 1.25	2.34 ± 1.08	*p* = 0.094	*p* = 0.430
1.3 mph	Intervention	3.57 ± 1.39	3.55 ± 1.39	F = 2.2;	F = 0.9;
	References	2.91 ± 1.39	2.33 ± 0.99	*p* = 0.142	*p* = 0.162
1.5 mph	Intervention	3.81 ± 1.45	3.58 ± 1.23	F = 1.4;	F = 0.1;
	Reference	2.57 ± 1.16	2.24 ± 0.96	*p* = 0.246	*p* = 0.833
1.7 mph	Intervention	3.86 ± 1.43	3.80 ± 1.19	F = 0.3;	F = 0.1;
	Reference	2.30 ± 0.97	2.10 ± 0.89	*p* = 0.565	*p* = 0.746
1.9 mph	Intervention	3.86 ± 1.53	4.05 ± 1.12	F = 0.1;	F = 0.9;
	Reference	2.49 ± 1.00	2.24 ± 0.85	*p* = 0.887	*p* = 0.330
Thorax transverse Rotation tROM(°)					
1.1 mph	Intervention	6.57 ± 2.83	8.35 ± 4.54	F = 7.5;	F = 1.6;
	Reference	7.34 ± 2.22	7.99 ± 2.84	***p* = 0.011**	*p* = 0.210
1.3 mph	Intervention	7.31 ± 3.30	9.00 ± 3.64	F = 7.9;	F = 1.5;
	Reference	6.98 ± 1.78	7.63 ± 2.67	***p* = 0.008**	*p* = 0.219
1.5 mph	Intervention	6.82 ± 2.50	9.40 ± 4.15	F = 20;	F = 7.4;
	Reference	6.76 ± 2.45	7.41 ± 2.58	***p* < 0.001**	***p* = 0.011**
1.7 mph	Intervention	7.19 ± 2.29	9.10 ± 3.63	F = 9.8;	F = 5.2;
	Reference	6.87 ± 2.16	7.17 ± 2.63	***p* = 0.004**	***p* = 0.030**
1.9 mph	Intervention	6.93 ± 2.39	9.82 ± 4.27	F = 12.7;	F = 9.1;
	Reference	6.59 ± 2.28	6.83 ± 2.25	***p* = 0.001**	***p* = 0.006**
Trunk transverse Rotation tROM(°)					
1.1 mph	Intervention	11.82 ± 3.86	15.48 ± 7.98	F = 3.45;	F = 3.13;
	Reference	12.97 ± 3.62	13.06 ± 3.54	*p* = 0.074	*p* = 0.088
1.3 mph	Intervention	13.35 ± 5.72	17.24 ± 7.11	F = 5.13;	F = 4.17;
	References	12.47 ± 3.15	12.67 ± 2.86	***p* = 0.031**	***p* = 0.050**
1.5 mph	Intervention	12.89 ± 4.30	17.84 ± 8.48	F = 9.25;	F = 6.47;
	References	12.13 ± 3.44	12.57 ± 3.05	***p* = 0.005**	***p* = 0.017**
1.7 mph	Intervention	13.56 ± 5.28	17.85 ± 7.87	F = 3.99;	F = 3.53;
	Reference	12.22 ± 3.39	12.32 ± 2.96	*p* = 0.055	*p* = 0.070
1.9 mph	Intervention	13.62 ± 4.71	17.86 ± 7.36	F = 4.12;	F = 5.05;
	Reference	12.39 ± 3.52	12.19 ± 2.61	*p* = 0.053	***p* = 0.034**

Note: Comparison of baseline and post-intervention between the two groups based on repeated measures ANOVA (Test × Group × Walking speeds).
Abbreviations: G – group; T – time; mph = miles per seconds; tROM = total Range of Motion; (°) = °.

$p = 0.070$, [ES] = 0.66, respectively) (Table 3).

No effect of training was found on stride time, stride length, and step width in both groups.

4. Discussion

The results of the present support in part our main hypotheses: unexpected perturbations exercises that evokes automatic balance responses while walking improves pelvic, thorax, and trunk transverse rotation at different gait speeds in older adults. Table 2, show that older adults that participated in perturbation training group had an average increase of 32% transverse pelvic rotation (from 6.05° to 7.98° $p = 0.017$), and 29% greater trunk transverse rotation (from 13.1° to 16.9° $p = 0.017$). These parameters have been shown in the past to be smaller in older adults compare with young's (Gimmon et al., 2015) and between fallers and non-fallers (Menz et al., 2003). This may suggest that the natural reduction of the lumbar spine mobility (i.e., trunk rotation) that occurs with aging was reversed by the training. The larger transvers pelvic rotation was not accompanied with a larger strides, this indicates that hip flexion during walking was shorter post training and that the contribution of the pelvic transverse rotation to step length was greater (i.e., "pelvic step"). Malatesta et al. (2003) found that young's perform pelvic transverse rotation, he suggested that this is a strategy to minimize COM vertical movements during the double support phase of gait and thus reduce energy costs during gait by reducing the COM, up and down (Malatesta et al., 2003; Lin et al., 2014). It seems that older adults of the perturbation training be able to learn how to minimize the vertical COM movement during gait by reducing hip flexion and a greater pelvic step. Smaller steps were found to reduce decreased COM vertical excursion, ground reaction force (GRF), shock attenuation and energy absorbed at the ankle, knee and hip joints (Schubert, Kempf, & Heiderscheit, 2014). A shorter hip flexion during the initial contact phase of gait cycle help to decrease in the AP horizontal ground reaction shear forces. This walking strategy may reduce the risk of slip during gait post perturbation training. By letting older adults learn explicitly how to recover from loss of balance during walking using step responses in a safe-controlled environment, they were able to adapt improve pelvic, trunk and thorax rotations, but not pelvic list rotation during treadmill gait.

Pai, Bhatt et al. (2014) speculated that during forward perturbation slip training the central nervous system (CNS) is able to make adaptive improvements in proactive and reactive control of stability as a result of trial and error. They argued that for successful recovery, the CNS builds internal representations to improve its feedforward control while walking. Our results confirm that older adults are able to adopt new walking patterns (i.e., "pelvic step"). Thus the beneficial effects after perturbation training are generalized to an improved proactive control of gait stability that may reduce fall risk in daily activities. The perturbation training applies the learning principle, which it is known to augment and to be generalizable (Schmidt & Lee, 1999). In real-life, inability to react properly to a balance loss (i.e., stepping response) can lead to a fall and injury; this and the fear of fall during the perturbation training may implicitly encourage the CNS to learn and remember movement strategies that reduce the risk of fall and to generalize to a stable walking pattern (Sacchetti, Scelfo, Tempia, & Strata, 2004), that may reduce falls (Pai, Bhatt, Yang, & Wang, 2004). It was suggested that the learning and generalization are reinforced by the unsuccessful trials that resulted from failed balance recovery. This is supported by several studies (Pai et al., 2004; Bhatt, Yang, & Pai, 2012; Bhatt, Yang, & Pai, 2011; Pai, Yang, Bhatt, & Wang, 2014) that found older adults showed significant retention of similar training effects, six and twelve months after training.

One important, practical, and promising finding is that gait can be trained and improved and that older adults are able to generalize skills that were learned during the unexpected perturbation training (i.e., evoked balance recovery) to different tasks, i.e., increase in pelvic, thorax, and trunk motion during gait. This expands our knowledge of the potential benefits of perturbation training in terms of its learning, generalizability, and specificity. We argue that the significant between-group difference in transverse pelvic, thorax, and trunk motion (Tables 2 and 3) may have been driven by unexpected loss of balance, when a large pelvic ROM is essential during the automatic recovery responses i.e., cross-over and lateral stepping responses require larger ROM than just walking. Therefore, it seems that there is a link between perturbation training and the ability of older adults to learn how to perform larger pelvic, thorax, and trunk motion during gait. This suggests that the adaptive improvements found in the intervention group appeared to be in proactive control, i.e., the positive effects on gait stability. The evidence seems to point to the conclusion that in perturbation training, proactive control can improve gait stability and may be generalizable across gait conditions, which have similar mechanisms of producing gait instability, possibly also outside of the training context. What is still unknown is how the improvement in treadmill walking carries over to real-life situations.

The control group subjects in our study were not exposed to unexpected loss of balance during walking and the automatic recovery responses were not evoked, thus large motion of pelvic and thorax was not required. The controls, however, also showed improvement as a result of training, specifically in thorax transverse motion. It was demonstrated previously that a gait training program that includes a verbal instruction to voluntarily move the arms and legs increased stride length, and larger pelvic and thorax rotations were made (i.e., explicit learning), which can improve pelvic and trunk ROM in stroke survivors (Ford, Wagenaar, & Newell, 2007).

The differences between unexpected perturbation training and self-initiated voluntary training (e.g., just walking) are fundamental. First, balance recovery responses following an external perturbation receive a higher priority than a voluntary action. Second, unexpected perturbation during walking closely mimics real life situations where balance is lost unexpectedly and automatic recovery response is initiated; thus proposing to implicitly encourage the CNS to learn and remember movement strategies (Sacchetti et al., 2004; Shadmehr & Mussa-Ivaldi, 1994). Third, these balance recovery strategies are not under volitional control and thus these strategies cannot be trained through self-initiated voluntary walking exercises. This concept may be of importance for balance and gait training and it further supports the notion that postural perturbations, especially during walking, should be incorporated into balance training programs. Fourth, it was suggested that inducing errors and triggering automatic balance responses to improve the effectiveness of protective recovery stepping, can be generalized to other untrained activities, such as walking. Going through such perturbation errors is vital for the CNS to regulate an existing internal representation of the environment (Shadmehr & Mussa-Ivaldi, 1994). This does not exist in self-initiated treadmill walking exercises in the control group. The control group training does not provide the opportunity for someone to improve pelvic and thorax ROM such as in situations that balance was lost unexpectedly. Our study included a control group who walked on the same perturbation system for the same number of trials and the same length of time but did not experience any unexpected loss of balance. Hence, in regard to pelvic and thorax motion we demonstrated that perturbation training during treadmill walking is better than treadmill walking only. This provides a higher order of evidence that demonstrates that exposure to perturbation training while walking to improve balance reactive responses is generalized to other functions, i.e., pelvic step walking, than training without exposure to unexpected loss of balance. Similar results were shown previously where repeated-slip training during a sit-to-stand task condition was generalized to an improvement in slip-induced falls during walking condition (Wang, Bhatt, Yang, & Pai, 2011). Also, older adults that traverse across the same slippery surface during training show improvement in "walkover" movement strategies (Bhatt, Wang, & Pai, 2006).

This study has limitations. First, this type of fall risk outcome (e.g., pelvic, thorax and trunk rotation) could be misleading due to our inability to make a strong link between these outcomes and falls. Second, the carryover impact of touch-mediated stabilization on balance ability during over-ground walking is not known. Third, the monitoring of falls in everyday living was conducted but the sample size for such analysis was too small, thus it is unknown whether the improvement carries over to real-life falls. Also we did not follow up the type of fall during the one-year follow-up, although it is logical that the perturbation-training paradigm would result in the large effects on slip- and trip-related falls in real life. Fourth, these findings are relevant only for relatively healthy independent non-faller older adults that did not fear falling, who probably are more likely to have a better neuro-plasticity and be able to recover safely; this cannot be generalized to more impaired and weak older adults. Finally, in our study older adults were exposed to 24 training sessions starting with a low dose (very low perturbations in the first session); we think that the optimum training would be exposure to a higher level of perturbation, those that resulted loss of balance during the baseline examination.

In conclusion, the results show carryover improvement in pelvic and trunk rotations while walking following perturbations treadmill training that drives balance recovery responses, and handrails are not used. These older adults had a more stable gait pattern with a lower ground reaction shear forces during the initial contact phase of gait cycle. This may lead to a decreased risk of falls in their everyday living.

Conflict of interest

IM and AS have developed and built the BaMPer perturbation system that was used in this project.

Author contributions

IK was involved in planning the experiments and conducting the intervention as well as data analysis and interpretation and drafting of the manuscript. YG was involved in conducting the Pre and Post intervention tests as well as data interpretation and drafting of the manuscript. AS was involved in experimental design, data interpretation and drafting of the manuscript. RD was involved in Subject recruitment, medical screening as well as drafting and revising of the manuscript. YS was involved in Subject recruitment, medical screening as well as drafting and revising of the manuscript. IM was involved in planning the experiments and conducting the Pre and Post intervention tests as well as data analysis and interpretation and drafting of the manuscript.

Sponsor's role

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