Gait & Posture 109 (2024) 126–132

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Action observation with motor simulation improves reactive stepping responses following strong backward balance perturbations in healthy young individuals

Lotte Hagedoorn [a,*], Aurora Ruiz Rodríguez [b], Edwin van Asseldonk [b], Vivian Weerdesteyn [a,c]

[a] Radboud university medical center; Donders Institute for Brain, Cognition and Behavior, Department of Rehabilitation, Nijmegen, The Netherlands
[b] University of Twente, Faculty of Engineering Technology, Enschede, The Netherlands
[c] Sint Maartenskliniek Research, Nijmegen, The Netherlands

ARTICLE INFO

Keywords:
Balance perturbations
Reactive stepping
First trial effect
Action observation with motor imagery
Action observation with motor simulation
Falls

ABSTRACT

Background and objective: Adequate reactive steps are critical for preventing falls following balance perturbations. Perturbation-based balance training was shown to improve reactive stepping in various clinical populations, but its delivery is labor-intensive and generally uses expensive equipment. Action observation of reactive steps with either motor imagery (AOMI) or motor simulation (AOMS) are potential alternative training modalities. We here aimed to study their effects on reactive stepping performance.
Methods: Sixty healthy young subjects were subjected to forward platform translations that elicited backward reactive steps. The AOMI group (n = 20) was tested after AOMI of an actor's reactive steps, while the AOMS group (n = 20) additionally stepped along with the actor. The control group (n = 20) was tested without any prior observation. Our primary outcome was the step quality of the first trial response, as this best represents a real-life loss-of-balance. Step quality was quantified as the leg angle with respect to the vertical at stepping-foot contact. We also studied single step success rates and reactive step quality across repeated trials.
Results: Reactive step quality was significantly better in the AOMI and AOMS groups than in the control group, which differences coincided with a twofold higher single step success rate. Reactive step quality improved upon repeated trials in all groups, yet the AOMS group needed the fewest repetitions to reach plateau performance.
Significance: The present results demonstrate that both AOMI and AOMS improved first and repeated trial reactive stepping performance. These findings point at the potential applicability of these concepts for home-based reactive balance training, for instance in serious games, with overt movements (AOMS) possibly having some benefits over mental imaginations (AOMI). Whether similar beneficial effects also emerge in the target populations of balance-impaired individuals remains to be investigated.

1. Introduction

The risk of falling is increased in older adults and people with neurological disorders [1–3]. Falls in daily life are often the result of inadequate reactive stepping performance, which is a final common balance saving strategy for preventing falls after an unexpected loss-of-balance [4]. Perturbation-based balance training (PBT) is an emerging rehabilitation intervention that has shown great potential for improving reactive stepping in various populations. In healthy older adults, fall rates were significantly reduced after PBT [5]. Moreover, gains in balance recovery performance were retained for weeks to months after training [6–8]. Incorporation of perturbation training into inpatient rehabilitation care of sub-acute stroke patients resulted in fewer falls in the six months post discharge [9], as well as in higher multistep thresholds and improved balance confidence [10]. Reactive step quality also improved following PBT in people with chronic stroke [11,12].

Despite this mounting evidence for the efficacy of PBT, there are significant limitations that prevent broad clinical uptake. To date, PBT often requires intensive supervision and specialized equipment. Therefore, this type of training is only available to a relatively limited number of patients. To tackle this issue, we wondered whether (partly) replacing real PBT practice by action observation with motor imagery (AOMI) of reactive stepping may be a viable option. This was inspired by

* Correspondence to: Department of Rehabilitation, Radboud university medical center, PO Box 9101, Nijmegen, 6500 HB, The Netherlands.
E-mail address: lotte.hagedoorn@radboudumc.nl (L. Hagedoorn).

https://doi.org/10.1016/j.gaitpost.2024.01.023
Received 8 July 2023; Received in revised form 22 December 2023; Accepted 18 January 2024
Available online 22 January 2024

neuroimaging studies demonstrating that brain activity patterns during action observation and motor imagery of e.g., hand gestures, locomotion and slipping - without performing an overt movement - correspond to those during actual task execution [13–16]. Furthermore, training programs using AOMI, either stand-alone or in addition to conventional training, have shown beneficial effects on balance and gait outcomes in healthy older adults [17–19] and people with chronic stroke [20,21]. Yet, the majority of these studies examined outcomes related to steady-state balance (e.g., postural oscillations) or to walking ability (e.g., Timed Up and Go test). Therefore, it remains to be investigated whether AOMI may be effective for improving reactive stepping responses as well.

To address this question, we aimed to investigate whether AOMI of reactive stepping (i.e., mentally imaging performing an observed reactive step) improves balance recovery responses following high-intensity backward perturbations in healthy young individuals, as compared to no prior action observation. We hypothesized that AOMI would prepare subjects better for new *real* balance perturbations and would thus result in a better reactive stepping performance, especially for the very first perturbation. In addition, we studied whether motor simulation, i.e., actually stepping along with the observed step as accurately as possible, may result in greater gains in reactive stepping performance compared to action observation with motor imagery alone.

2. Methods

2.1. Participants

Sixty healthy young adults (23.7 ± 3.1 years; 36 females) participated in the study (Table 1). Exclusion criteria were any neurological, orthopedic or vestibular disorder or use of medication negatively affecting balance, and any prior experience with balance perturbations induced by the Radboud Fall Simulator (RFS) or with other experimentally induced balance perturbations. All subjects gave written informed consent prior to participation. The study was conducted in accordance with the Declaration of Helsinki and adhered to the guidelines of the local medical ethical committee (CMO region Arnhem-Nijmegen).

2.2. Experimental setup

The experiments were conducted using the RFS, which is a movable platform (Baat Medical, Enschede, The Netherlands) with two integrated force plates (0.6 × 1.8 m each, AMTI Custom 6 axis composite force platform, USA) that delivered strong perturbations. Backward balance perturbations were delivered by platform translations in forward direction. Perturbations comprised of an acceleration (4.5 m/s^2, 300 ms), constant velocity (1.35 m/s, 500 ms), and a deceleration phase (−4.5 m/s^2, 300 ms). Participants stood barefoot on the platform with their feet 4.5 cm apart and wore a safety harness attached to the ceiling to prevent falling. The perturbation direction was known in advance and the onset of perturbation randomly varied between 3 to 6 s. Participants were instructed to respond to the perturbations with a single step without grabbing the rails surrounding the platform.

There were three different groups: a control group (CTR), an action observation with motor imagery group (AOMI) or an action observation with motor simulation group (AOMS) (Fig. 1a). Participants were allocated at random. They were all subjected to a series of 20 *real* balance perturbations in the backward direction. The CTR group was tested without any prior observation of a third person (actor) reacting to the same series of perturbations. Before being subjected to the perturbations themselves, the AOMI group was instructed to attentively observe the actor's movements in response to the same series of 20 perturbations and to mentally imagine themselves performing the reactive steps in the same manner (Fig. 1b). The AOMS group was additionally instructed to move along with the actor as accurately as possible in terms of step timing, size and direction. Standardized instructions were read aloud from paper by the researcher. The participant and the actor were instructed to not communicate with each during the experiment. Only the participant, the actor (if applicable) and the researcher were present during the session.

2.3. Data acquisition and analysis

Ground reaction forces (GRFs) underneath each foot were collected by the two force plates integrated in the moveable platform (sampled at 2000 Hz). The vertical force components from each force plate were filtered offline at 20 Hz with a 10th order zero-lag Butterworth filter. Reflective markers were placed on anatomical landmarks according to the Vicon Lower Body Plugin-Gait model (Vicon Motion Systems, United Kingdom). An additional reflective marker was placed on the platform to correct marker positions for platform movements. The marker positions were recorded by an 8-camera 3D motion analysis system (sampled at 100 Hz, Vicon Motion Systems, United Kingdom). Marker trajectory data were filtered offline with a 10 Hz low-pass 2nd order zero-lag Butterworth filter. Perturbation onset was encoded by a digital trigger signal (sampled at 1000 Hz). The moments of foot off and foot contact were detected from the ground reaction forces, using a threshold value of 100 N. Small shuffling movements of the foot (i.e. both vertical heel lift and horizontal heel displacement both below 5 cm) were not considered as steps. In those cases, the first 'real' step was included in the analysis. Single steps were defined as steps where no further expansion of the base of support occurred in the direction of the perturbation after first foot contact . Single step success was visually evaluated and manually annotated during data acquisition and verified using video-recordings.

2.4. Outcomes

The primary outcome was reactive step quality of the first *real* perturbation trial, which is considered to best represent an unexpected real-life loss-of-balance [22]. Step quality was defined as the leg angle at first stepping-foot contact; it was computed as the angle between the vertical and the line connecting the mid-pelvis with the second metatarsal of the stepping-foot (Fig. 1c). A positive leg angle represents a foot position posterior to the vertical and larger positive leg angles correspond to better step quality [11].

The success rate of recovering balance with a single step (as instructed) in the first trial was determined as a secondary outcome measure. In addition, we calculated the following secondary outcomes measures to investigate step characteristics that could explain possible differences in first trial performance. We calculated step onset, step duration, step length, step velocity and total mid-pelvis excursion (i.e. from perturbation onset to first stepping-foot contact) to gain insight in

Table 1
Participants' Characteristics.

	CTR (n = 20)	AOMI (n = 20)	AOMS (n = 20)	*p*-value
Age (mean ± SD)	23.6 ± 3.7	23.2 ± 2.6	24.3 ± 3.2	0.57
Gender (male/female)	11/9	5/15	6/14	0.11

CTR, control group; AOMI, action observation with motor imagery group; AOMS, action observation with motor simulation group. There were no significant differences between groups in age and gender (assessed with an one-way ANOVA and a $\chi 2$ test, respectively).

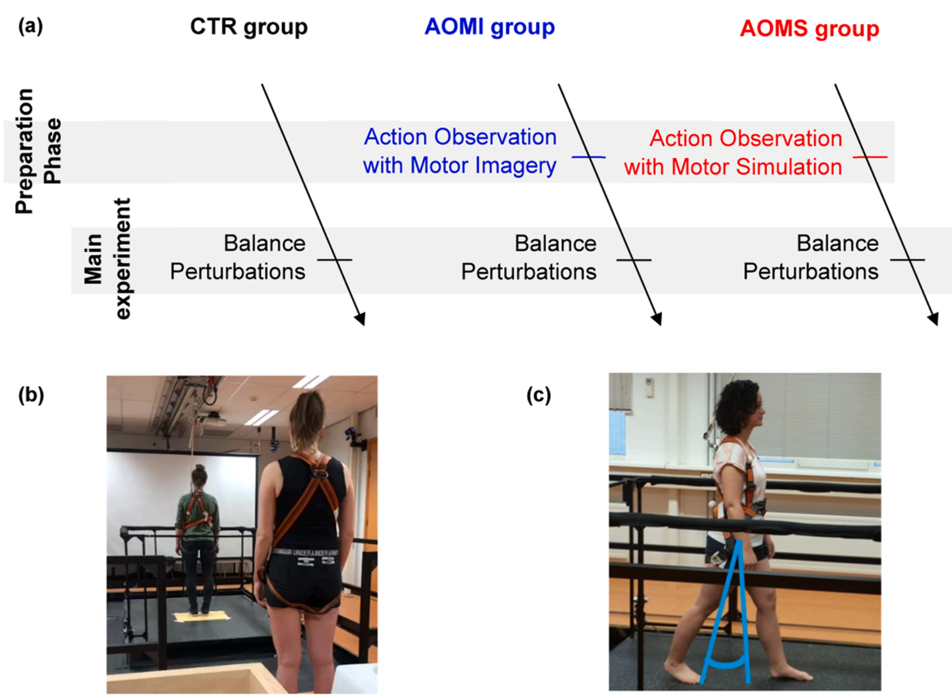

Fig. 1. Overview of experimental protocol. **a)** Participants were allocated to a control group (CTR), an action observation with motor imagery group (AOMI) or an action observation with motor simulation group (AOMS) to prepare for the main experiment consisting of a sequence of 20 high-intensity backward balance perturbations. **b)** Photo illustrating the AOMI phase. The participant stood behind the Radboud Fall Simulator (RFS) and observed and mentally imagined the reactive stepping movements of the other person on the RFS. **c)** Definition of the leg angle, the primary outcome measure, for a backward step. Reactive step quality was expressed as the leg angle at stepping-leg contact.

the characteristics of the first step. To study whether participants anticipated to the first perturbation by adopting a more favorable initial posture for counteracting the expected impact, we calculated forward lean and weight-bearing asymmetry [23,24]. Forward lean at perturbation onset was calculated as the distance between the mid-pelvis and the line connecting the heel markers, expressed as a percentage of the length of the BoS. Weight-bearing asymmetry in favor of the stance leg was calculated as the mean GRF of the stance leg over the 500 ms time interval pre perturbation onset, expressed as percentage of the total body weight. Lastly, to verify whether the initial passive effect of the perturbation on the CoM dynamics was similar across groups, we calculated the velocity of the mid-pelvis at 150 ms post perturbation onset before any active corrective response was expected to take place [25]. All step characteristics were calculated in the sagittal plane.

Lastly, the leg angle was determined for all subsequent trials to investigate whether participants improved their reactive step quality over the course of repeated perturbations. All outcome measures were calculated with custom-written Matlab software (version R2022a).

2.5. Statistical analysis

The leg angle in the first trial, as well as the secondary outcomes of the first trial, were compared between groups using the non-parametric Kruskal-Wallis H test (due to non-normal distributions), with post-hoc Mann-Whitney U tests in case of a significant effect of group. The number of steps required (i.e., single step or multiple steps) in the first trial was compared between groups with a Pearson χ^2 test. To investigate whether participants improved their reactive step quality over the course of repeated perturbations, we used linear mixed model analyses for repeated categorical observations to study within group changes in leg angle as function of repeated perturbations. The average leg angle over the last five trials was defined as the reference leg angle, so the factor Trial consisted of sixteen levels (trial 1 to 15 individually and trial 16 to 20 averaged). Post-hoc pairwise comparisons with Bonferroni correction for multiple comparisons were performed to contrast the leg angle in each of the first fifteen trials to the reference leg angle. Statistical analyses were performed with SPSS (version 25) with a significance level of $\alpha = 0.05$.

3. Results

3.1. First trial response

One first trial of a subject in the AOMS group was excluded from analysis, because the platform slightly moved backward before the actual forward translation, which warned the participant for the upcoming perturbation. The leg angle in the very first trial significantly differed between groups ($H(2) = 9.363$, $p = 0.009$) (Fig. 2a). The first trial leg angle was significantly higher in both the AOMI group (12.5° [8.2–14.4] (median [Q1-Q3]), $U = 108$, $p = 0.012$) and the AOMS group (11.7° [9.2–15.8], $U = 91$, $p = 0.005$) compared to the CTR group (6.5° [2.4–10.4]). There was no significant difference in the first trial leg angle between the AOMS group and the AOMI group ($U = 179$, $p = 0.771$).

Only 25% of the participants in the CTR group were able to recover balance with a single step following the first perturbation (Fig. 2b), whereas more than half of the participants in the AOMI and AOMS groups (50% and 58%, respectively) did recover in one step (CRT versus AOMI, $\chi(1) = 2.667$, $p = 0.102$; CTR versus AOMS, $\chi(1) = 4.358$, $p = 0.037$).

Table 2 summarizes the secondary first trial outcomes. There was a significant group effect on step length ($H(2) = 9.928$, $p = 0.007$), step velocity ($H(2) = 6.395$, $p = 0.041$), total mid-pelvis excursion ($H(2) = 6.608$, $p = 0.037$) and forward lean ($H(2) = 19.505$), $p < 0.001$). Larger values were observed in both AOMI and AOMS groups compared with the CTR group, but did not differ between the AOMI and AOMS group. Step onset, step duration, mid-pelvis velocity and weight-bearing asymmetry were not significantly different between groups.

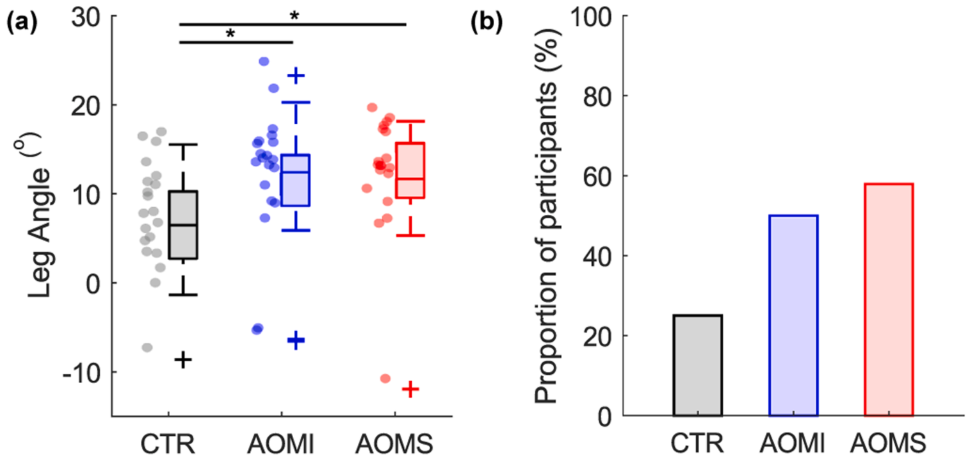

Fig. 2. First trial step response, represented by **a)** the leg angle and **b)** the proportion of participants that succeeded with a single step. Significant differences ($p < 0.05$) between groups are indicated with asterisks (*).

Table 2
First trial characteristics.

		Median [Q1-Q3]			Kruskal-Wallis	
		CTR (n = 20)	AOMI (n = 20)	AOMS (n = 19)	H(2)	*p*-value
Spatiotemporal	Step onset (ms)	259 [235–275]	263 [252–292]	261 [245–306]	1.292	0.524
	Step duration (ms)	222 [201–247]	234 [203–257]	236 [208–252]	0.957	0.620
	Step length (cm)	55 [44–59]	62 [57–65]	64 [57–70]	9.928	**0.007***
	Step velocity (cm/s)	240 [203–260]	260 [240–288]	260 [240–320]	6.395	**0.041***
	Total MidPelvis excursion (cm)	30 [28–35]	36 [32–40]	37 [32–38]	6.608	**0.037***
Anticipation	Forward lean (%BoS)	50 [46–58]	67 [64–71]	64 [58–68]	19.51	**<0.001***
	Weightbearing asymmetry (%BW)	54 [50–57]	53 [48–56]	54 [52–61]	2.831	0.243
Passive effect	MidPelvis velocity at 150 ms (mm/s)	44 [41–48]	44 [41–45]	45 [43–47]	3.531	0.171

* CTR < AOMI and CTR < AOMS, assessed with post-hoc Mann-Whitney U tests ($p < 0.05$). CTR, control group; AOMI, action observation with motor imagery group; AOMS, action observation with motor simulation group; Q1, first quartile; Q3, third quartile; BoS, base of support; BW, body weight.

3.2. Repeated trial response

First, we verified that the reference leg angle (i.e., the average leg angle over the last five trials) did not differ significantly between groups ($H(2) = 0.819$, $p = 0.664$). In all three groups, the leg angle improved over the course of repeated perturbations (see Fig. 3), as demonstrated by a significant effect of Trial number in the CTR ($F(15) = 9.5$, $p < 0.001$), AOMI ($F(15) = 12.2$, $p < 0.001$) and AOMS group ($F(15) = 13.4$, $p < 0.001$).

Post-hoc analysis revealed significant differences between the reference leg angle and one or more of the fifteen preceding trials in each of the groups (Fig. 4). In the AOMS group, the mean leg angle was lower

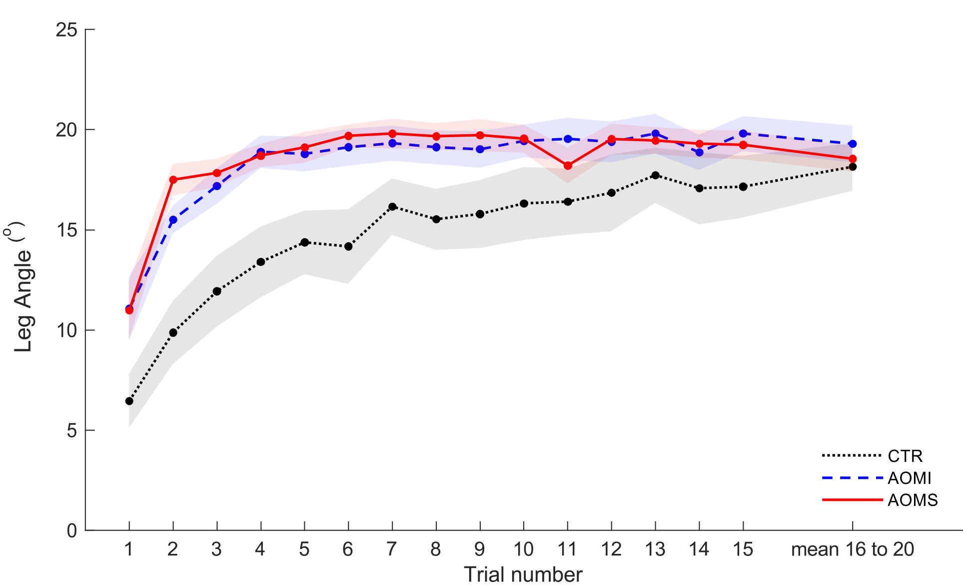

Fig. 3. Time course of improvement in leg angle over repeated perturbations. Dots represent the mean leg angles across subjects and shaded areas represent the standard error of the mean.

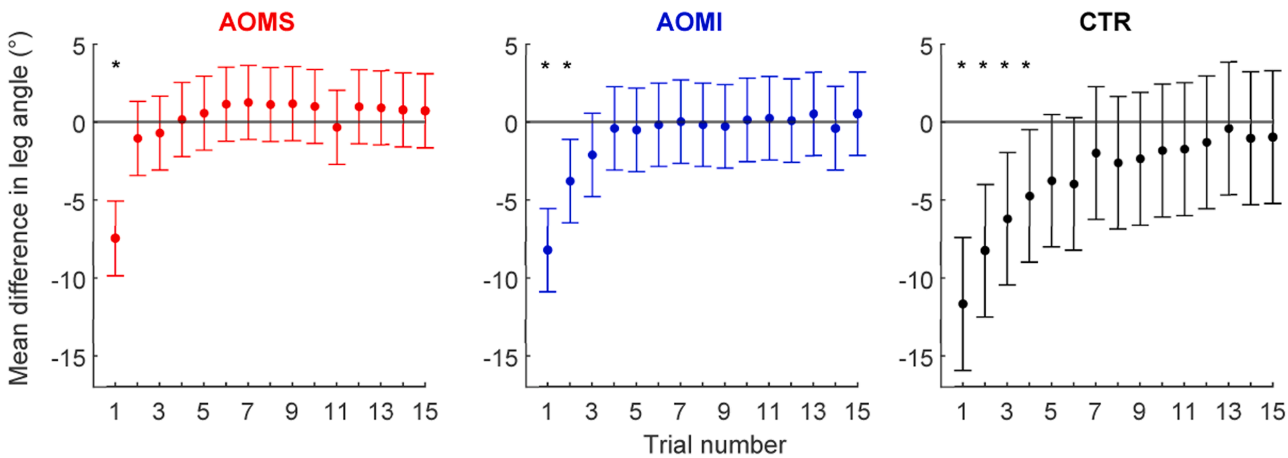

Fig. 4. Estimated marginal mean differences in leg angle per group, showing differences between the reference leg angle (i.e., the average leg angle over de last five trials) and each of the fifteen preceding trials. Means and 95% confidence intervals are shown.

than the reference leg angle only in the very first trial (−7.5°(95 %CI [−9.9,−5.1]), $p < 0.001$). In the AOMI group, the mean leg angle was significantly lower than the reference leg angle in the first two trials (trial 1, −8.2°[−10.9,−5.6], $p < 0.001$; trial 2, −3.8°[−6.5,−1.1], $p < 0.001$). In the CTR group, the leg angle was significantly lower than the reference leg angle in trials 1 to 4 (trial 1, −11.7°[−16.0,−7.4], $p < 0.001$; trial 2, −8.3°[−12.5,−4.0], $p < 0.001$, trial 3, −6.2°[−10.5,−2.0], $p < 0.001$; trial 4, −4.7°[−9.0,−0.5], $p = 0.016$), while trials 5 and 6 bordered significance (−3.8°[−8.0,0.5] and −4.0°[−8.2,0.3], respectively).

4. Discussion

The goal of this study was to investigate whether action observation of reactive steps with either motor imagery or motor simulation may help improve reactive stepping performance in response to novel perturbations. As hypothesized, both AOMI and AOMS resulted in better reactive stepping performance following the very first perturbation, as demonstrated by a larger leg angle at foot contact. In addition, these first trial reactive steps were of greater length and velocity, which differences coincided with a twofold higher single step success rate. Moreover, both AOMI and AOMS yielded faster gains in step quality upon repeated perturbations compared to CTR, with AOMS showing the fastest improvement.

4.1. First trial response

Our finding of improved first trial responses following AOMI and AOMS is of particular relevance, as such a novel perturbation is ecologically more valid and quantitatively different than subsequent trials [22]. The relevance of the first trial effect size (i.e., a 4.5° greater mean leg angle) is supported by the observation that it was found along with a higher probability of successful recovery, with a previous study reporting a three-fold greater odds of successful recovery for every 1° increment in leg angle [25]. For comparison, the currently observed effect size is of the same order of magnitude as the observed gains in leg angle following a 10-sessions perturbation-based training program in people with stroke (4.3° [11]).

The better first trial responses following AOMI and AOMS may be related to reduced startle reflexes. The first trial response is thought to consist of a superimposition of active corrective balance responses and the startle reflex [26]. Startle reflexes, i.e., involuntary motor reactions to unexpected sensory inputs, limit the effectiveness of the response during new and unexpected balance perturbations [26,27], due to increased joint stiffness from extensive generalized coactivity across bilateral muscles [27]. We speculate that prior AOMI and AOMS may have prevented strong startle reflexes from the novel first perturbation, thus enhancing the effectiveness of active balance correcting responses. Yet, as the actual experience of the loss-of-balance induced by the perturbation remained new, first trial performance in the AOMI and AOMS groups was not yet optimal, as demonstrated by further improvements in reactive steps with repeated exposure.

The greater first trial leg angles after AOMI or AOMS were found along with larger step lengths and higher step velocities, which outcomes are indeed strongly correlated [25,28]. Of note, we also observed a ~6 cm greater mid-pelvis excursions after prior observation, whereas step onset and duration did not differ between groups. Since the leg angle depends on both the mid-pelvis and the stepping-foot position, the greater pelvis excursion would theoretically oppose the effects of the larger step length and velocity on the leg angle. Yet, this difference was observed along with AOMI and AOMS participants leaning more forward in anticipation of the perturbation, thus reducing its impact [23]. The difference in forward lean corresponded to a forward displacement of the mid-pelvis of approximately 3 cm (i.e. half the difference in total mid-pelvis excursion). According to an inverted pendulum model, this distance accounts for a difference in leg angle of approximately 1.8°, which is much lower than the observed between-group mean difference in first trial leg angles (~4.5°). We therefore conclude that, in addition to potential benefits of anticipatory forward lean, the reactive step itself was indeed qualitatively better following AOMI or AOMS.

4.2. Repeated trial response

The naive participants in the present study gradually increased their leg angles over the course of the experiment and eventually achieved plateau performance. This is in line with a previous study in which the probability of successful recovery increased with repeated very large perturbations in naïve healthy young adults, which was found along with gains in leg angles [25]. AOMI participants reached plateau performance faster than CTR subjects (in the third vs. fifth trial), whereas AOMS participants reached plateau performance already in the second trial. We reasoned that learning from motor simulation, where an actual step is performed - albeit voluntary in nature - could be situated between learning from motor imagery (no execution of a step) and learning from physical practice (execution of a true reactive step, e.g., during PBT). This is supported by our results, although differences with AOMI were modest.

4.3. Limitations and future directions

A limitation was that the study was conducted in healthy young participants, whereas the risk of falls is particularly relevant in older adults and in neurologically impaired persons [29]. While it has previously been shown that these groups can indeed improve motor skills from AOMI [17–22], it remains for future studies to investigate whether this also holds for reactive stepping in the target populations of PBT.

In the present study, backward reactive step quality was assessed after AOMI or AOMS of reactive steps evoked in the same direction. However, perturbations in daily life are unpredictable regarding their direction and intensity. Previous studies demonstrated the generalization of acquired motor adaptation across different physical perturbations [30,31]. Moreover, the response after AOMI or AOMS manifested a greater proactive component than would be the case in real-life perturbations, as participants already had some prior knowledge. Whether the beneficial effects of AOMI or AOMS for a single direction and intensity also generalize across other perturbation directions and intensities remains to be investigated. If this would be the case, this would greatly enhance the potential of embedding AOMI or AOMS in reactive balance training.

4.4. Clinical implications

Real balance perturbations cannot be safely trained at home. Based on the present findings, solutions for home-based reactive balance training, for instance in the form of exergames, may be developed to exploit the potential of AOMI and AOMS. Such serious games may be valuable for complementing standard rehabilitation therapy, as well as for its continuation at home after discharge [32]. The use of AOMS may have benefits over AOMI, since it elicits overt movements (rather than just mental imaginations), which is expected to increase home-user engagement [33]. Therefore, AOMS in particular may hold promise for enabling home-based training of reactive balance in populations with an increased risk of falling, such as people with chronic stroke, but this requires further research.

CRediT authorship contribution statement

Vivian Weerdesteyn: Conceptualization, Funding acquisition, Methodology, Project administration, Writing – review & editing. **Lotte Hagedoorn:** Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Edwin van Asseldonk:** Funding acquisition, Supervision, Writing – review & editing. **Aurora Ruiz Rodríguez:** Writing – review & editing.

Declaration of Competing Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgments

This work was supported by the Netherlands Organisation for Health Research and Development (ZonMW) and the Dutch CardioVascular Alliance (DVCA), DCVA-IMDI-UA grant (n. 104021002 project HEROES) and by the Netherlands Organization for Scientific Research (NWO), VIDI grant awarded to VW (n. 91717369, project Roads to recovery). We thank Geert van Bon, Ghita Puts and Karen Braspenning for their help with the data collection.

References

[1] V. Weerdesteyn, M. de Niet, H.J. van Duijnhoven, A.C. Geurts, Falls in individuals with stroke, J. Rehabil. Res. Dev. 45 (8) (2008) 1195–1213.
[2] F.A. Batchelor, S.F. Mackintosh, C.M. Said, K.D. Hill, Falls after stroke, Int. J. Stroke 7 (6) (2012) 482–490, https://doi.org/10.1111/j.1747-4949.2012.00796.x.
[3] J.M.B. Roelofs, I.M. Schut, A.C.M. Huisinga, A.C. Schouten, H.T. Hendricks, F.E. de Leeuw, et al., Minor stroke, serious problems: the impact on balance and gait capacity, fall rate and physical activity, (Submitted).
[4] B.E. Maki, W.E. McIlroy, Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention, Age Ageing 35 (Suppl 2) (2006) ii12–ii18, https://doi.org/10.1093/ageing/afl078.
[5] M.H.G. Gerards, C. McCrum, A. Mansfield, K. Meijer, Perturbation-based balance training for falls reduction among older adults: current evidence and implications for clinical practice, Geriatr. Gerontol. Int. 17 (12) (2017) 2294–2303, https://doi.org/10.1111/ggi.13082.
[6] X. Liu, T. Bhatt, S. Wang, F. Yang, Y.C. Pai, Retention of the "first-trial effect" in gait-slip among community-living older adults, Geroscience 39 (1) (2017) 93–102, https://doi.org/10.1007/s11357-017-9963-0.
[7] T. Bhatt, F. Yang, Y.C. Pai, Learning to resist gait-slip falls: long-term retention in community-dwelling older adults, Arch. Phys. Med. Rehabil. 93 (4) (2012) 557–564, https://doi.org/10.1016/j.apmr.2011.10.027.
[8] Y.C. Pai, F. Yang, T. Bhatt, E. Wang, Learning from laboratory-induced falling: long-term motor retention among older adults, Age (Dordr.) 36 (3) (2014) 9640, https://doi.org/10.1007/s11357-014-9640-5.
[9] A. Mansfield, A. Schinkel-Ivy, C.J. Danells, A. Aqui, R. Aryan, L. Biasin, et al., Does perturbation training prevent falls after discharge from stroke rehabilitation? A prospective cohort study with historical control, J. Stroke Cereb. Dis. 26 (10) (2017) 2174–2180, https://doi.org/10.1016/j.jstrokecerebrovasdis.2017.04.041.
[10] S. Handelzalts, M. Kenner-Furman, G. Gray, N. Soroker, G. Shani, I. Melzer, Effects of perturbation-based balance training in subacute persons with stroke: a randomized controlled trial, Neurorehabil. Neural. Repair. 33 (3) (2019) 213–224, https://doi.org/10.1177/1545968319829453.
[11] H.J.R. van Duijnhoven, J.M.B. Roelofs, J.J. den Boer, F.C. Lem, R. Hofman, G.E. A. van Bon, et al., Perturbation-based balance training to improve step quality in the chronic phase after stroke: a proof-of-concept study, Front. Neurol. 9 (2018) 980, https://doi.org/10.3389/fneur.2018.00980.
[12] A. Schinkel-Ivy, A.H. Huntley, A. Aqui, A. Mansfield, Does perturbation-based balance training improve control of reactive stepping in individuals with chronic stroke? J. Stroke Cereb. Dis. 28 (4) (2019) 935–943, https://doi.org/10.1016/j.jstrokecerebrovasdis.2018.12.011.
[13] T. Bhatt, P. Patel, S. Dusane, S.R. DelDonno, S.A. Langenecker, Neural mechanisms involved in mental imagery of slip-perturbation while walking: a preliminary fMRI study, Front. Behav. Neurosci. 12 (2018) 203, https://doi.org/10.3389/fnbeh.2018.00203.
[14] R.M. Hardwick, S. Caspers, S.B. Eickhoff, S.P. Swinnen, Neural correlates of action: comparing meta-analyses of imagery, observation, and execution, Neurosci. Biobehav Rev. 94 (2018) 31–44, https://doi.org/10.1016/j.neubiorev.2018.08.003.
[15] E. Gerardin, A. Sirigu, S. Lehericy, J.B. Poline, B. Gaymard, C. Marsault, et al., Partially overlapping neural networks for real and imagined hand movements, Cereb. Cortex 10 (11) (2000) 1093–1104, https://doi.org/10.1093/cercor/10.11.1093.
[16] C. la Fougere, A. Zwergal, A. Rominger, S. Forster, G. Fesl, M. Dieterich, et al., Real versus imagined locomotion: a[18F]-FDG PET-fMRI comparison, Neuroimage 50 (4) (2010) 1589–1598, https://doi.org/10.1016/j.neuroimage.2009.12.060.
[17] M.F. Hamel, Y. Lajoie, Mental imagery. Effects on static balance and attentional demands of the elderly, Aging Clin. Exp. Res. 17 (3) (2005) 223–228, https://doi.org/10.1007/BF03324601.
[18] M. Goudarzian, S. Ghavi, A. Shariat, H. Shirvani, M. Rahimi, Effects of whole body vibration training and mental training on mobility, neuromuscular performance, and muscle strength in older men, J. Exerc Rehabil. 13 (5) (2017) 573–580, https://doi.org/10.12965/jer.1735024.512.
[19] W. Taube, M. Lorch, S. Zeiter, M. Keller, Non-physical practice improves task performance in an unstable, perturbed environment: motor imagery and observational balance training, Front. Hum. Neurosci. 8 (2014) 972, https://doi.org/10.3389/fnhum.2014.00972.
[20] H.Y. Cho, J.S. Kim, G.C. Lee, Effects of motor imagery training on balance and gait abilities in post-stroke patients: a randomized controlled trial, Clin. Rehabil. 27 (8) (2013) 675–680, https://doi.org/10.1177/0269215512464702.
[21] S.A. Hosseini, M. Fallahpour, M. Sayadi, M. Gharib, H. Haghgoo, The impact of mental practice on stroke patients' postural balance, J. Neurol. Sci. 322 (1-2) (2012) 263–267, https://doi.org/10.1016/j.jns.2012.07.030.
[22] J.H. Allum, K.S. Tang, M.G. Carpenter, L.B. Oude Nijhuis, B.R. Bloem, Review of first trial responses in balance control: influence of vestibular loss and Parkinson's disease, Hum. Mov. Sci. 30 (2) (2011) 279–295, https://doi.org/10.1016/j.humov.2010.11.009.
[23] M. Stokkermans, T. Solis-Escalante, M.X. Cohen, V. Weerdesteyn, Midfrontal theta dynamics index the monitoring of postural stability, Cereb. Cortex (2022), https://doi.org/10.1093/cercor/bhac283.
[24] D. de Kam, J.F. Kamphuis, V. Weerdesteyn, A.C. Geurts, The effect of weight-bearing asymmetry on dynamic postural stability in healthy young individuals, Gait Posture 45 (2016) 56–61, https://doi.org/10.1016/j.gaitpost.2016.01.004.
[25] V. Weerdesteyn, A.C. Laing, S.N. Robinovitch, The body configuration at step contact critically determines the successfulness of balance recovery in response to large backward perturbations, Gait Posture 35 (3) (2012) 462–466, https://doi.org/10.1016/j.gaitpost.2011.11.008.
[26] J. Nonnekes, M.G. Carpenter, J.T. Inglis, J. Duysens, V. Weerdesteyn, What startles tell us about control of posture and gait, Neurosci. Biobehav Rev. 53 (2015) 131–138, https://doi.org/10.1016/j.neubiorev.2015.04.002.
[27] A. Sawers, Y.C. Pai, T. Bhatt, L.H. Ting, Neuromuscular responses differ between slip-induced falls and recoveries in older adults, J. Neurophysiol. 117 (2) (2017) 509–522, https://doi.org/10.1152/jn.00699.2016.
[28] D. de Kam, J.M.B. Roelofs, A.C.H. Geurts, V. Weerdesteyn, Body configuration at first stepping-foot contact predicts backward balance recovery capacity in people

with chronic stroke, PLoS One 13 (2) (2018) e0192961, https://doi.org/10.1371/journal.pone.0192961.

[29] D. de Kam, J.M.B. Roelofs, A. Bruijnes, A.C.H. Geurts, V. Weerdesteyn, The next step in understanding impaired reactive balance control in people with stroke: the role of defective early automatic postural responses, Neurorehabil Neural Repair 31 (8) (2017) 708–716, https://doi.org/10.1177/1545968317718267.

[30] T. Bhatt, T.Y. Wang, F. Yang, Y.C. Pai, Adaptation and generalization to opposing perturbations in walking, Neuroscience 246 (2013) 435–450, https://doi.org/10.1016/j.neuroscience.2013.04.013.

[31] S. Wang, Y.C. Pai, T. Bhatt, Neuromuscular mechanisms of motor adaptation to repeated gait-slip perturbations in older adults, Sci. Rep. 12 (1) (2022) 19851, https://doi.org/10.1038/s41598-022-23051-w.

[32] J.M. Veerbeek, E. van Wegen, R. van Peppen, P.J. van der Wees, E. Hendriks, M. Rietberg, et al., What is the evidence for physical therapy poststroke? A systematic review and meta-analysis, PLoS One 9 (2) (2014) e87987, https://doi.org/10.1371/journal.pone.0087987.

[33] R. Essery, A.W. Geraghty, S. Kirby, L. Yardley, Predictors of adherence to home-based physical therapies: a systematic review, Disabil. Rehabil. 39 (6) (2017) 519–534, https://doi.org/10.1007/978-1-4419-1428-6_453.