Human Movement Science 76 (2021) 102775

Contents lists available at ScienceDirect

Human Movement Science

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

Full Length Article

Repeated exposure to tripping like perturbations elicits more precise control and lower toe clearance of the swinging foot during steady walking

Tamon Miyake [a,*], Federica Aprigliano [b], Shigeki Sugano [a], Silvestro Micera [b,c], Vito Monaco [b]

[a] Graduate School of Creative Science and Engineering, Waseda University, Tokyo, Japan
[b] The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
[c] Bertarelli Foundation Chair in Translational NeuroEngineering, Center for Neuroprosthetics and Institute of Bioengineering, School of Engineering, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland

ARTICLE INFO

Keywords:
Minimum toe clearance
Tripping
Locomotion
Perturbation
Falling

ABSTRACT

Controlling minimum toe clearance (MTC) is considered an important factor in preventing tripping. In the current study, we investigated modifications of neuro-muscular control underlying toe clearance during steady locomotion induced by repeated exposure to tripping-like perturbations of the right swing foot. Fourteen healthy young adults (mean age 26.4 ± 3.1 years) participated in the study. The experimental protocol consisted of three identical trials, each involving three phases: steady walking (baseline), perturbation, and steady walking (post-perturbation). During the perturbation, participants experienced 30 tripping-like perturbations at unexpected timing delivered by a custom-made mechatronic perturbation device. The temporal parameters (cadence and stance $phase_{\%}$), mean, and standard deviation of MTC were computed across approximately 90 strides collected during both baseline and post-perturbation phases, for all trials. The effects of trial (three levels), phase (two levels: baseline and post-perturbation) and foot (two levels: right and left) on the outcome variables were analyzed using a three-way repeated measures analysis of variance. The results revealed that exposure to repeated trip-like perturbations modified MTC toward more precise control and lower toe clearance of the swinging foot, which appeared to reflect both the expectation of potential forthcoming perturbations and a quicker compensatory response in cases of a lack of balance. Moreover, locomotion control enabled subjects to maintain symmetric rhythmic features during post-perturbation steady walking. Finally, the effects of exposure to perturbation quickly disappeared among consecutive trials.

1. Introduction

Balance control during walking aims at achieving steady gait patterns and preventing falling. Lack of balance and falling are indeed serious health issues, causing injuries and reduction of independence in older people and physically fragile individuals (Ayoung-Chee et al., 2014). Tripping is one of the main causes of falls (Timsina et al., 2017), and is usually caused by unintentional contact of the

* Corresponding author at: Graduate School of Creative Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo, Japan.
E-mail address: tamon-tamonc3@ruri.waseda.jp (T. Miyake).

https://doi.org/10.1016/j.humov.2021.102775
Received 3 May 2020; Received in revised form 26 November 2020; Accepted 16 February 2021
Available online 22 February 2021

swinging foot against an obstacle (e.g., carpet). Minimum toe clearance (MTC) at the mid-swing phase is a critical parameter related to tripping (Barrett, Mills, & Begg, 2010; Begg, Best, Dell'Oro, & Taylor, 2007; Blake et al., 1988; Winter, 1992). Accordingly, understanding how humans control MTC is an important issue in designing suitable strategies to decrease the fall risk due to tripping.

Average (mean or median) MTC and the related variability (e.g., standard deviation, inter-quartile range) are determined by the individuals' attitudes regarding the control of toe clearance (Killeen et al., 2017). Specifically, a low variability of MTC suggests accurate neuromuscular control of toe clearance (Begg et al., 2007; Mills, Barrett, & Morrison, 2008; Moosabhoy & Gard, 2006) while a lower average MTC reflects increased attention or cognitive workload during the task being performed (Killeen et al., 2017; Schulz, Lloyd, & Lee, 2010).

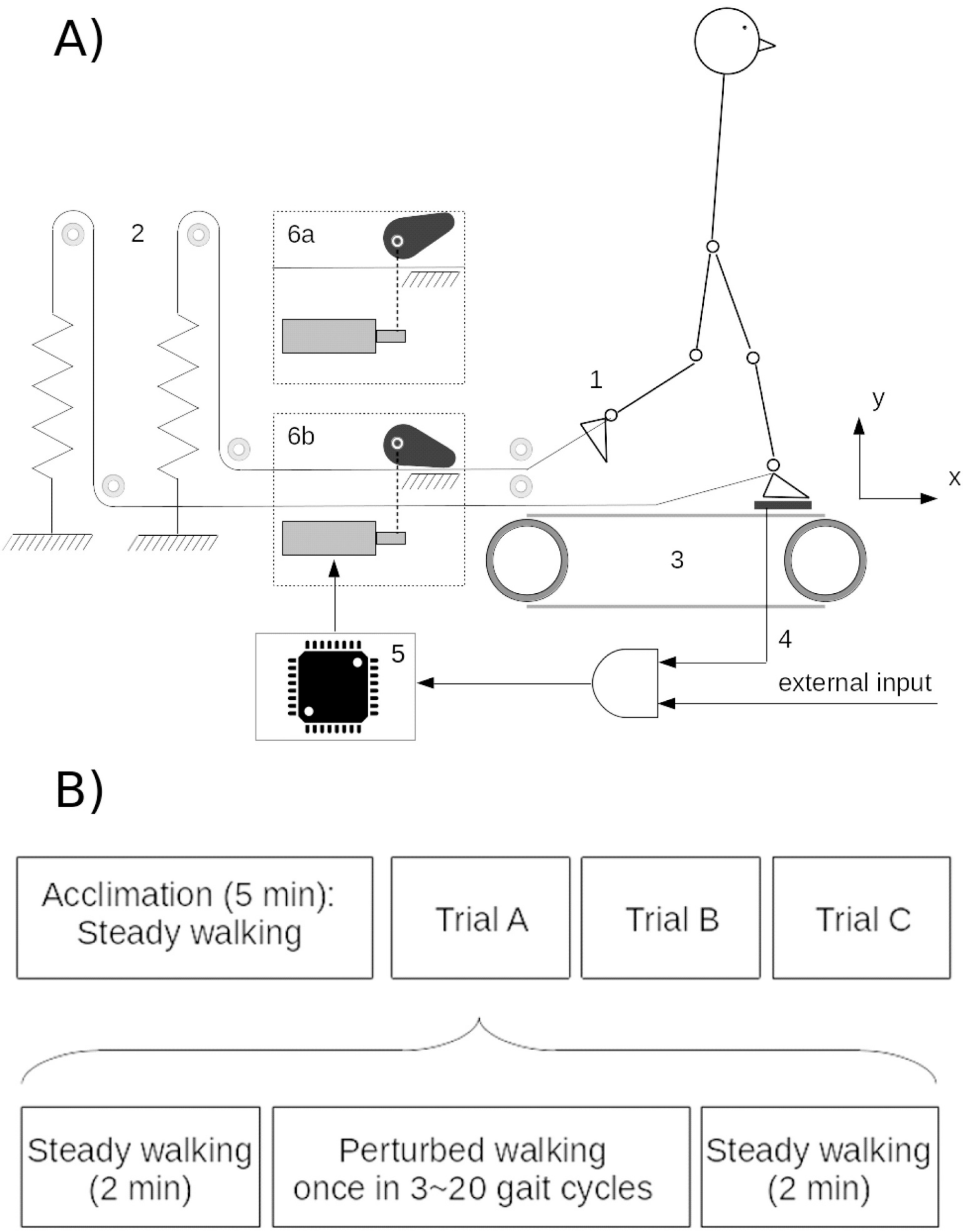


Fig. 1. Schematic representation of the experimental setup and protocol. (A) Labelled components of the experimental setup are respectively: 1. perturbed foot; 2. spring-rope mechanism; 3. treadmill; 4. signal coming from the foot switch under the unperturbed foot; 5. Microcontroller driving the motor connected to the cam; 6a. cam-based mechanism while the rope can freely move; 6b. cam-based mechanism while the rope is stopped. (B) The experimental protocol consisted of: a preliminary acclimation period where participants walked steadily at their self-selected speed; three equal trials (1st, 2nd, and 3rd trials), each accounting for an initial 2 min long steady walking period (baseline), followed by a perturbing phase, and concluding with a 2 min long steady walking period (post-training).

Previous studies have revealed that either visual inputs or concomitant motor and cognitive tasks, namely Stroop tasks, can adaptively modify the MTC, thus altering the control of toe clearance (Begg et al., 2014; Killeen et al., 2017; Mills et al., 2008). However, one of the open questions concerns the hypothesis that repeated exposure to tripping can modify the neuro-muscular control underlying toe clearance as well, as an alternative strategy to visual feedback or Stroop tasks. Perturbation-based paradigms have been indeed reported to promote motor adaptation following unexpected balance loss (Aprigliano et al., 2019; Martelli, Vashista, Micera, & Agrawal, 2016; McCrum, Gerards, Karamanidis, Zijlstra, & Meijer, 2017) and reduce the overall number of falls (Lurie, Zagaria, Pidgeon, Forman, & Spratt, 2013; Pai, Bhatt, Yang, & Wang, 2014). Although previous studies have analyzed biomechanical behavior during unexpected tripping (Aprigliano, Micera, & Monaco, 2019; Dario, Martin, & André, 2020; Pijnappels, Bobbert, & van Dieen, 2005; Roos, McGuigan, & Trewartha, 2010; Shirota, Simon, & Kuiken, 2014) or adaptation during repeated exposure to obstacle avoidance (Bhatt, Wang, Yang, & Pai, 2013; Wang, Bhatt, Yang, & Pai, 2012), to the best of our knowledge, the effects of repeated exposure to tripping on MTC control have not been exhaustively investigated.

The aim of this study was to investigate modifications of foot control during the swing phase of steady locomotion as a consequence of repeated exposure to tripping-like perturbations. Specifically, we first tested the hypothesis that the mean and standard deviation of MTC during steady walking would increase and decrease, respectively, after the perturbation. Second, we tested the hypothesis that a series of perturbation sessions can further increase the mean value of MTC and decrease its variability during the swing phase of steady locomotion. This hypothesis grounds on the evidence that when re-experiencing perturbations, the learning process can be faster and sometimes more effective thanks to memory-based mechanisms (Huang, Haith, Mazzoni, & Krakauer, 2011; Mawase, Shmuelof, Bar-Haim, & Karniel, 2014). Finally, we tested the hypothesis that mono-lateral (only right) perturbations can comparably modify the behavioral control of both feet, as a consequence of bilateral coupling of neural control (Dietz, 2002; Dietz & Schrafl-Altermatt, 2016). As matter of fact, unilateral motor practice has been shown to transfer behavioral benefits in the untrained limb (Carroll, Herbert, Munn, Lee, & Gandevia, 2006; Farthing, 2009; Ruddy & Carson, 2013). Accordingly, we expected a similarly altered foot control of both perturbed and unperturbed limbs after the training.

2. Materials and methods

2.1. Participants and experimental setup

Fourteen healthy young adults (seven females and seven males; 26.4 ± 3.1 years; 63.4 ± 8.5 kg; 1.72 ± 0.09 m) were enrolled in the study after providing written informed consent. Participants had no evidence or known history of postural, musculo-skeletal or neurological diseases.

The experimental setup was widely described in one of our previous studies (Aprigliano, Micera, & Monaco, 2019), and will be briefly depicted as follows. It consisted of a treadmill provided with a custom-made perturbation device designed to interrupt the swinging limb by a rope attached to the foot, thus likely emulating tripping (Fig. 1A). During steady walking, the rope moved forward or backward, through a series of pulleys, according to the movement of the foot. When activated, the rope was stopped by the cam mechanism and prevented the foot from moving forward along the swing phase, emulating tripping. To avoid gait asymmetries, the perturbation device was equipped with two rope-spring systems even though the one connecting the unperturbed foot did not account for any cam-braking mechanism.

The control architecture of the perturbation device was based on an Arduino Due microcontroller. The controller managed two different inputs: (i) an external enabler, handled by the experimenter, and (ii) the signal from a footswitch under the unperturbed foot revealing the heel strike. When the experimenter, who was not visible to the participant, decided to deliver the perturbation, she/he activated the control loop by means of the external input. The cam-based actuation then started moving when the heel strike of the unperturbed foot was detected. Once activated, the cam moved from the starting position to the rope (300 ms), stopped the rope movement (300 ms), and then, released it. The rope braking was timed to likely occur during the mid-swing phase, that is, when the toe clearance is minimum and the risk of tripping is higher.

For safety purposes, the treadmill was equipped with handrails, which participants were instructed to grasp only in cases of unrecoverable lack of balance. Otherwise, they were not allowed to use the handrails during the experimental session.

The 3D trajectory of 25 body landmarks was recorded at 100 Hz using a six-camera motion capture system (Vicon 512 Bonita 10 Motion Analysis System, Oxford, U.K.). Markers were located on segments of the lower limbs (i.e., pelvis, thighs, shanks and feet), as reported elsewhere (Aprigliano et al., 2017).

2.2. Experimental protocol

Before the experimental sessions, participants were asked to steadily walk on the treadmill for 5 min at their preferred speed (0.90 ± 0.08 m/s) for acclimation (Fig. 1B). The preferred walking speed was identified by increasing/decreasing the belt velocity until participants reported feeling confident. Three initial perturbations at mid-swing were delivered at random times to prevent excessive reactions due to the unknown postural unbalance, namely first trial effects (Nijhuis et al., 2009). No data were collected during this period.

Subsequently, participants were involved in the first of three identical trials, named 1st, 2nd, and 3rd trial, in which they were informed that their gait could be perturbed (Fig. 1B). Each trial consisted of three phases:

- first, during the initial 2 min (baseline), subjects walked steadily at their preferred speed while their lower limb kinematics was recorded; no perturbations were delivered during this phase;
- second, while walking, participants underwent 30 mid-swing perturbations of the right foot (herein the term "perturbed foot" will always refer to the right one); perturbations were delivered at random times every 3–20 strides; the second phase was approximately 6 min long;
- finally (post-perturbation), participants continued walking for 2 more minutes until we asked them to stop, while their lower limb kinematics was recorded; no perturbations were delivered during this phase.

To prevent proactive adjustments due to external cues, participants listened to music (a playlist accounting for songs with different tempi to prevent entrainment) via headphones, and did not know when perturbations would have been delivered. The duration of each trial was approximately 10 min, and participant wore their own gymnastic shoes.

Between consecutive trials, the participants were allowed to rest on a chair until they felt ready for the next trial. Overall, the duration of the entire experimental session (i.e., acclimation, three trials, and two resting phases) was less than 1 h.

2.3. Data analysis

Kinematic data were evaluated offline using the Vicon software (NexusMotion Capture Software). Missing data were interpolated using a build-in function of gap filling. The 3D kinematics data were then exported and pre-processed in the MATLAB (The MathWorks, Inc., Natick, MA, USA) environment. Specifically, raw data were smoothed with a low pass filter (cutoff at 10 Hz) to reduce high frequency noise. The cutoff frequency was set according to the procedure described elsewhere (Winter, 2005). Only data related to feet

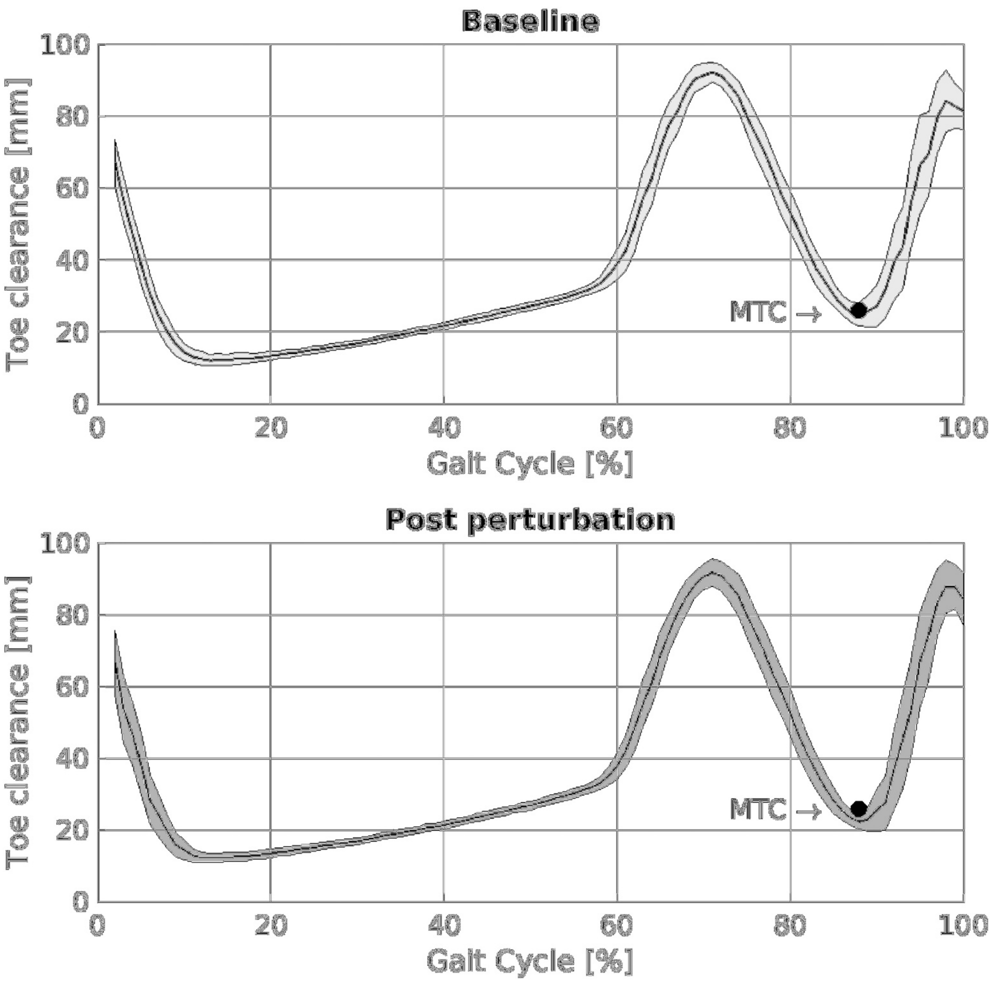


Fig. 2. Representative example of the Toe Clearance, i.e., the vertical component of the first metatarsal head (mean ± 1 standard deviation, across 90 strides), recorded during the baseline and post-perturbation of the first trial. X-axis describes the percentage of the gait cycle (0% is the heel strike, 100% is the next heel strike). The Minimum Toe Clearance (MTC) of baseline during the swing phase (about 90% of the gait cycle) is highlighted by a black dot marker.

markers (i.e., heel, first and fifth metatarsal heads) during steady walking before and after the perturbations (i.e., baseline and post-perturbation) were retained for further analysis.

For each trial, data related to steady locomotion, before (i.e., baseline) and after (i.e., post-perturbation) the perturbation session, were used to identify three main time events:

- the heel strike, as the local minimum of the vertical component of the marker on the heel;
- the toe off, as the local minimum of the antero-posterior component of the marker on the first metatarsal head;
- the time during the swing phase that corresponded to the minimum toe clearance (MTC), as the local minimum of the vertical component of the marker on the first metatarsal head (Fig. 2).

To evaluate whether the perturbations altered gait dynamics, for each subject, the mean cadence and duration of the stance phase (as percentage of the gait cycle, $stance_{\%}$) across all strides, for each walking condition (i.e., baseline and post-perturbation, 1st, 2nd, and 3rd trials), for both feet, were considered representative temporal metrics for that specific participant. For each subject, the mean and the standard deviation of the MTC, namely MTC_{av} and MTC_{SD}, across all strides, for each walking condition and both feet, were considered representative metrics for that specific participant. Overall, approximately 90 strides were collected both before and after each perturbation session (baseline and post-perturbation, respectively).

2.4. Statistical analysis

Outcome variables (cadence, $stance_{\%}$, MTC_{av} and MTC_{SD}) were used as dependent measures. A three-way repeated measures Analysis Of Variance (ANOVA) was undertaken to observe main and interaction effects of factors trials (three levels: 1st, 2nd, and 3rd), recorded phases (two levels: baseline and post-perturbation) and observed foot (two levels: perturbed-right and unperturbed-left foot), on the outcome variables. In case of significant main effects, the ANOVA test was followed-up by the pairwise comparisons with Bonferroni method. The statistical significance level was set at $p < 0.05$.

3. Results

3.1. Minimum toe clearance

Results of the three-way ANOVA revealed a significant main effect of factors of perturbation and observed foot on both MTC_{av} and MTC_{SD} ($p_{phases} < 0.05$ and $p_{foot} < 0.05$ in Table 1, Fig. 3). In particular, MTC_{av} and MTC_{SD} decreased after the perturbation-based training and were higher on the right (i.e., perturbed) foot. More in detail: for the left (i.e. unperturbed) foot, MTC_{av} decreased from 31.1 ± 9.1 mm to 28.5 ± 8.1 mm while MTC_{SD} decreased from 3.0 ± 1.0 mm to 2.7 ± 0.7 mm across the training; for the right (i.e., perturbed) foot, MTC_{av} decreased from 32.7 ± 8.5 mm to 30.7 ± 8.6 mm while MTC_{SD} decreased from 3.3 ± 1.0 mm to 2.9 ± 0.8 mm across the training.

No interaction effects were observed among factors (i.e., trial, phases and foot) for MTC_{av} and MTC_{SD} (all *p*-values >0.05, Table 1).

3.2. Temporal parameters

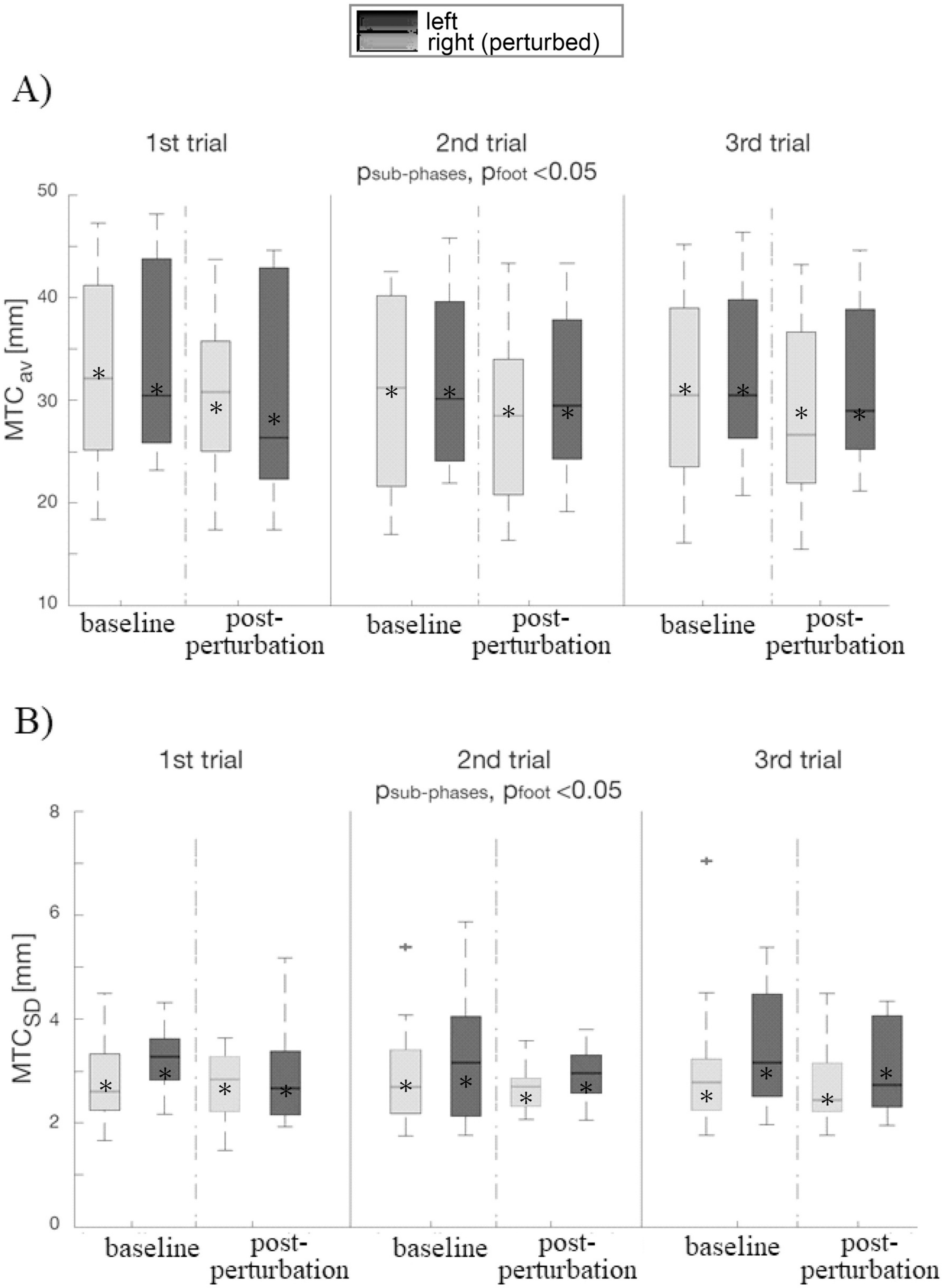
The statistical analysis performed on temporal parameters revealed that the exposure to repeated perturbations did not affect cadence and $stance_{\%}$ across trials and phases (p_{trials} and $p_{phases} > 0.05$ in Table 1, Fig. 4). In addition, no significant effect was identified for the observed foot ($p_{foot} > 0.05$, Table 1). Finally, no interaction effects were observed among factors (i.e., trial, phases and foot) for cadence and $stance_{\%}$ (all p-values >0.05, Table 1).

4. Discussion

In this study, we investigated the modifications of foot control during the swing phase of steady locomotion as a consequence of repeated exposure to tripping-like perturbations. As expected, after perturbation, participants showed more precise control of the

Table 1
Results of the 3-way ANOVA performed on the observed variables (cadence, stance%, MTCav, MTC_{SD}). The *p*-values of the main and interaction effects of the trial (3 levels: 1st, 2nd and 3rd), the recorded phases (2 levels: baseline and post-perturbation) and the observed feet (2 levels: right and left) are reported. *P*-values <0.05 are in bold.

p-values	cadence	$stance_{\%}$	MTC_{av}	MTC_{SD}
p_{trial}	0.088	0.293	0.633	0.611
p_{phases}	0.397	0.228	**0.001**	**0.009**
p_{foot}	0.787	0.132	**0.006**	**0.012**
$p_{trial*phases}$	0.541	0.337	0.764	0.702
$p_{trial*foot}$	0.961	0.276	0.746	0.994
$p_{phases*foot}$	0.801	0.291	0.617	0.507
$p_{trial*phases*foot}$	0.981	0.299	0.822	0.968



(caption on next page)

Fig. 3. **(A)** Boxplot of the mean Minimum Toe Clearance across strides (MTC_{av}), for each trial (i.e., 1st, 2nd, and 3rd), both phases (i.e., baseline and post-perturbation), and both feet (i.e., right and left, dark and light grey, respectively). **(B)** Boxplot of the standard deviation of the Minimum Toe Clearance across strides (MTC_{SD}), for each trial (i.e., 1st, 2nd, and 3rd), both phases (i.e., baseline and Post-perturbation), and both feet (i.e., right and left, dark and light grey, respectively). Horizontal lines represent medians, outliers (data points falling more than 1.5 interquartile range, above the third quartile or below the first quartile) are displayed using '+', means are highlighted by "*".

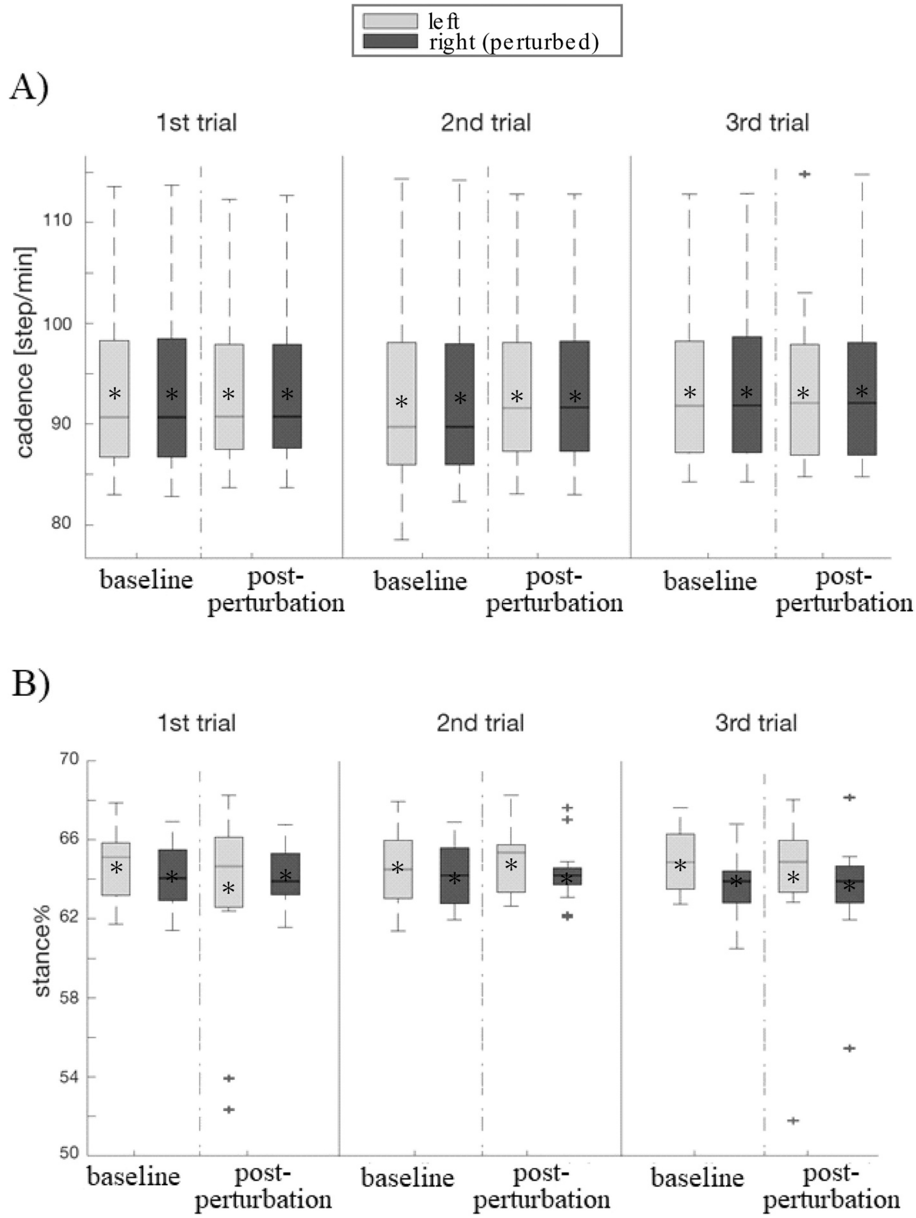


Fig. 4. **(A)** Boxplot of the cadence, for each trial (i.e., 1st, 2nd, and 3rd), both phases (i.e., baseline and post-perturbation), and both feet (i.e., right and left, dark and light grey, respectively). **(B)** Boxplot of the duration of the stance phase, as a percentage of the gait cycle, for each trial (i.e., 1st, 2nd, and 3rd), both phases (i.e., baseline and post-perturbation), and both feet (i.e., right and left, dark and light grey, respectively). Horizontal lines represent medians, outliers (data points falling more than 1.5 interquartile range, above the third quartile or below the first quartile) are displayed using '+', means are highlighted by "*".

swinging foot (i.e., MTC_{SD} decreased after perturbation, Fig. 3A), even if the hypothesis that MTC_{av} increases after perturbation was rejected. The results also rejected the hypotheses that MTC_{av} and MTC_{SD} increased and decreased, respectively, along the trials, and that mono-lateral (only right) perturbations can differently modify the behavioral control of feet. Noticeably, we did not observe any change in temporal parameters (Fig. 4 and Table 1) across experimental conditions. Therefore, we can confidently state that the overall dynamics of locomotion was not perturbed by the experimental paradigms while change in MTC_{av} and MTC_{SD} likely reflect specific control strategies.

Exposure to tripping-like perturbations, as in our experimental paradigm, involved short-term adaptations consisting of decreased toe clearance (MTC_{av}; Fig. 3A and Table 1) and MTC variability (i.e., MTC_{SD}; Fig. 3B and Table 1). It is worth noting that similar lowering behavioral modifications have been reported in previous studies, where subjects were asked to simultaneously walk steadily and carry out a cognitive task (Killeen et al., 2017; Mills et al., 2008; Schulz et al., 2010). This apparent similarity might suggest that our experimental paradigm involved depletion of attentional resources, thus leading participants to adopt a more automated strategy to control the swinging foot, possibly mediated by the lower part of the central nervous system (Killeen et al., 2017).

We instead believe that the observed short-term adaptations (i.e., decreased MTC_{av} and MTC_{SD}) likely reflected a volitional strategy for speeding up an effective contralateral compensatory step. This strategy is usually named lowering strategy and has been observed when people are tripped in the mid-late swing phase (Forner, Koopman, & van der Helm, 2003; Schillings, van Wezel, Mulder, & Duysens, 2000). In particular, the smaller the foot clearance, the shorter the time required to lower the foot to the ground and to rely on the contralateral compensatory step. In this respect, the reduced MTC average and variability would suggest a finer control of the swinging foot, enabling a rapid reliance on the unperturbed limb in case of a forthcoming perturbation.

Our results also revealed that the effects of exposure to the series of perturbations decayed quickly during the period of rest, such that participants adopted the same naive foot control during the swing phase at the beginning of each session (i.e., for each baseline; Fig. 3 and Table 1). These results support the assumption that modifications of MTC_{av} and MTC_{SD} early after each perturbation session were mainly due to the expectation of potential forthcoming perturbations, thus reflecting volitional modifications of foot control during the swing phase.

Previous studies investigating the effects of repeated exposure to obstacle avoidance, as a possible cause of tripping, revealed that, after the perturbation, people *increase* their toe clearance even during steady walking, in order to reduce possible trip-induced instabilities (Bhatt et al., 2013; Wang et al., 2012). Noticeably, this strategy, namely elevating strategy, can be observed in the perturbed foot in case of an early tripping (Shirota, Simon, & Kuiken, 2015), or repeated perturbations (Bhatt et al., 2013; Wang et al., 2012). In addition, a direct volitional control of the foot to *increase* the toe clearance has been well documented in subjects while attempting to cross visible or hidden obstacles (Schulz, 2011), or in cases of visual restriction or blurring (Graci, Elliott, & Buckley, 2009; Killeen et al., 2017).

In spite of this, in our study we observed a finer control of the foot to *decrease* its clearance (i.e., smaller MTC_{av} and MTC_{SD}) as short-term adaptation to the proposed experimental paradigm. Accordingly, the behavior is expected to augment the probability of tripping. Therefore, we can conclude that an experimental paradigm based on a foot pulling strategy might not be suitable if used to train people to prevent tripping.

We believe that the difference among studies is mainly due to the different perturbation paradigm. In particular, all studies agree that subjects can adapt their motor behavior to repeated perturbations, both obstacle avoidance and foot pulling. However, adaptations following the former perturbation paradigm can differ significantly from those observed during the latter, thus reflecting the flexibility of human balance control across different sensory-motor contexts (Aprigliano et al., 2017). In addition, these results suggest that motor adaptations underlying the direct control of toe clearance can be differentially modulated by the predictability of the perturbation timing obtained with visual and proprioceptive inputs. Visual inputs elicit proactive control strategies, involving increased toe clearance, to prevent unexpected alterations of the full body dynamics due to tripping (Graci et al., 2009; Killeen et al., 2017; Schulz, 2011). In contrast, when only proprioceptive information is available and the perturbation timing cannot be predicted, as in our experimental paradigm, subjects decrease toe clearance control to promote a quicker contralateral step to counteract the lack of balance.

Another important result in this study concerns the effects of mono-lateral perturbations on the toe clearance control of both feet. Specifically, we hypothesized that after the perturbation (i.e., during steady locomotion), subjects would show symmetrical neuromuscular adaptations involving similar toe clearance between limbs based on the transfer between trained and untrained limb noticed in earlier studies (Carroll et al., 2006; Farthing, 2009; Ruddy & Carson, 2013). Despite this, our results indicated that the unperturbed foot (i.e., left foot) was controlled more finely (i.e., lower MTC_{SD}) toward a lower toe clearance (i.e., lower MTC_{av}) than the perturbed one during the post-perturbation steady walking session. This asymmetrical behavior further corroborates the idea that neuromuscular adaptation post-perturbation allows subjects to promptly react to unexpected perturbations by relying on a quick shift between the perturbed and unperturbed limbs. Thus, more precise toe control of the left foot is expected to involve a faster response of the unperturbed limb, thereby promoting balance recovery based on bipedal support. Consequently, the observed adaptive post-perturbation behavior reflects the flexibility of the locomotor control system, which allows subjects to maintain symmetric rhythmic features (i.e., cadence and $stance_{\%}$) while implementing asymmetric control of toe clearance between the two feet to maximize the effectiveness of the reactive response in case of unexpected tripping.

5. Conclusions

Repeated exposure to tripping modifies average and standard deviation of MTC toward lower toe clearance and lower variance of the swinging foot. These adaptive modifications appear to both reflect the expectation of potential forthcoming perturbations and promote a quicker compensatory response in the case of forthcoming perturbation. In addition, although the adopted perturbation paradigm involves asymmetric behavior between limbs, locomotion control allowed subjects to maintain symmetric rhythmic features (i.e., cadence and $stance_{\%}$) during post-perturbation steady walking. This result provides further support for the evidence that the neuromuscular system can adaptively and flexibly implement control strategies aimed at meeting a twofold goal, such as maintaining symmetric rhythmic features of the gait cycle while ensuring a faster shift to the unperturbed limb to recovery balance.

Acknowledgments

This work was supported by: the Program for Leading Graduate Schools, “Graduate Program for Embodiment Informatics” of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan; the EU Commission through the H2020 project CYBERLEGs Plus Plus (The CYBERnetic LowEr-Limb CoGnitive Ortho-prosthesis Plus Plus, Grant Agreement no. 731931); the Italian National Institute for Insurance against accidents at work (INAIL) within the MOTU project (PPR-AI 1-2); Grants-in-Aid for Scientific Research of the Japan Society for the Promotion of Science (19J14599).

References

Aprigliano, F., Martelli, D., Kang, J., Kuo, S. H., Kang, U. J., Monaco, V., … Agrawal, S. K. (2019). Effects of repeated waist-pull perturbations on gait stability in subjects with cerebellar ataxia. *Journal of Neuroengineering and Rehabilitation, 16*, 50.

Aprigliano, F., Martelli, D., Tropea, P., Pasquini, G., Micera, S., & Monaco, V. (2017). Aging does not affect the intralimb coordination elicited by slip-like perturbation of different intensities. *Journal of Neurophysiology, 118*, 1739–1748.

Aprigliano, F., Micera, S., & Monaco, V. (2019). Pre-impact detection algorithm to identify tripping events using wearable sensors. *Sensors, 19*, 3713.

Ayoung-Chee, P., McIntyre, L., Ebel, B. E., Mack, C. D., McCormick, W., & Maier, R. V. (2014). Long-term outcomes of ground-level falls in the elderly. *The Journal of Trauma and Acute Care Surgery, 76*, 498–503.

Barrett, R. S., Mills, P. M., & Begg, R. K. (2010). A systematic review of the effect of ageing and falls history on minimum foot clearance characteristics during level walking. *Gait & Posture, 32*, 429–435.

Begg, R., Best, R., Dell'Oro, L., & Taylor, S. (2007). Minimum foot clearance during walking: Strategies for the minimisation of trip-related falls. *Gait & Posture, 25*, 191–198.

Begg, R. K., Tirosh, O., Said, C. M., Sparrow, W. A., Steinberg, N., Levinger, P., & Galea, M. P. (2014). Gait training with real-time augmented toe-ground clearance information decreases tripping risk in older adults and a person with chronic stroke. *Frontiers in Human Neuroscience*, 8.

Bhatt, T., Wang, T. Y., Yang, F., & Pai, Y. C. (2013). Adaptation and generalization to opposing perturbations in walking. *Neuroscience, 246*, 435–450.

Blake, A. J., Morgan, K., Bendall, M. J., Dallosso, H., Ebrahim, S. B. J., Arie, T. H. D., … Bassey, E. J. (1988). Falls by elderly people at home - prevalence and associated factors. *Age and Ageing, 17*, 365–372.

Carroll, T. J., Herbert, R. D., Munn, J., Lee, M., & Gandevia, S. C. (2006). Contralateral effects of unilateral strength training: Evidence and possible mechanisms. *Journal of Applied Physiology, 101*, 1514–1522.

Dario, T., Martin, G., & André, S. (2020). Review of balance recovery in response to external perturbations during daily activities. *Human Movement Science, 69*, 2020.

Dietz, V. (2002). Do human bipeds use quadrupedal coordination? *Trends in Neurosciences, 25*, 462–467.

Dietz, V., & Schrafl-Altermatt, M. (2016). Control of functional movements in healthy and post-stroke subjects: Role of neural interlimb coupling. *Clinical Neurophysiology, 127*, 2286–2293.

Farthing, J. P. (2009). Cross-education of strength depends on limb dominance: Implications for theory and application. *Exercise and Sport Sciences Reviews, 37*, 179–187.

Forner, C. A., Koopman, H. F., & van der Helm, F. C. (2003). Multiple-step strategies to recover fromstumbling perturbations. *Gait & Posture, 18*, 47–59.

Graci, V., Elliott, D. B., & Buckley, J. G. (2009). Peripheral visual cues affect minimum-foot-clearance during overground locomotion. *Gait & Posture, 30*, 370–374.

Huang, V. S., Haith, A., Mazzoni, P., & Krakauer, J. W. (2011). Rethinking motor learning and savings in adaptation paradigms: model-free memory for successful actions combines with internal models. *Neuron, 70*, 787–801.

Killeen, T., Easthope, C. S., Demko, L., Filli, L., Lorincz, L., Linnebank, M., … Bolliger, M. (2017). Minimum toe clearance: Probing the neural control of locomotion. *Scientific Reports, 7*.

Lurie, J. D., Zagaria, A. B., Pidgeon, D. M., Forman, J. L., & Spratt, K. F. (2013). Pilot comparative effectiveness study of surface perturbation treadmill training to prevent falls in older adults. *BMC Geriatrics, 13*.

Martelli, D., Vashista, V., Micera, S., & Agrawal, S. K. (2016). Direction-dependent adaptation of dynamic gait stability following waist-pull perturbations. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 24*, 1304–1313.

Mawase, F., Shmuelof, J., Bar-Haim, S., & Karniel, A. (2014). Savings in locomotor adaptation explained by changes. *Journal of Neurophysiology, 111*, 1444–1454.

McCrum, C., Gerards, M. H. G., Karamanidis, K., Zijlstra, W., & Meijer, K. (2017). A systematic review of gait perturbation paradigms for improving reactive stepping responses and falls risk among healthy older adults. *European Review of Aging and Physical Activity, 14*.

Mills, P. M., Barrett, R. S., & Morrison, S. (2008). Toe clearance variability during walking in young and elderly men. *Gait & Posture, 28*, 101–107.

Moosabhoy, M. A., & Gard, S. A. (2006). Methodology for determining the sensitivity of swing leg toe clearance and leg length to swing leg joint angles during gait. *Gait & Posture, 24*, 493–501.

Nijhuis, L. B. O., Allum, J. H. J., Borm, G. F., Honegger, F., Overeem, S., & Bloem, B. R. (2009). Directional sensitivity of “first trial” reactions in human balance control. *Journal of Neurophysiology, 101*, 2802–2814.

Pai, Y. C., Bhatt, T., Yang, F., & Wang, E. (2014). Perturbation training can reduce community-dwelling older adults' annual fall risk: A randomized controlled trial. *The Journals of Gerontology Series A Biological Sciences and Medical Sciences, 69*, 1586–1594.

Pijnappels, M., Bobbert, M. F., & van Dieen, J. H. (2005). Push-off reactions in recovery after tripping discriminate young subjects, older non-falters and older fallers. *Gait & Posture, 21*, 388–394.

Roos, P. E., McGuigan, M. P., & Trewartha, G. (2010). The role of strategy selection, limb force capacity and limb positioning in successful trip recovery. *Clinical biomechanics, 25*, 873–878.

Ruddy, K. L., & Carson, R. G. (2013). Neural pathways mediating cross education of motor function. *Frontiers in Human Neuroscience, 7*, 397.

Schillings, A. M., van Wezel, B. M., Mulder, T., & Duysens, J. (2000). Muscular responses and movementstrategies during stumbling over obstacles. *Journal of Neurophysiology, 83*, 2093–2102.

Schulz, B. W. (2011). Minimum toe clearance adaptations to floor surface irregularity and gait speed. *Journal of Biomechanics, 44*, 1277–1284.

Schulz, B. W., Lloyd, J. D., & Lee, W. E. (2010). The effects of everyday concurrent tasks on overground minimum toe clearance and gait parameters. *Gait & Posture, 32*, 18–22.

Shirota, C., Simon, A. M., & Kuiken, T. A. (2014). Trip recovery strategies following perturbations of variable duration. *Journal of Biomechanics, 47*, 2679–2684.

Shirota, C., Simon, A. M., & Kuiken, T. A. (2015). Transfemoral amputee recovery strategiesfollowing trips to their sound andprosthesis sides throughout swing phase. *Journal ofNeuroEngineering and Rehabilitation, 12*, 79.

Timsina, L. R., Willetts, J. L., Brennan, M. J., Marucci-Wellman, H., Lombardi, D. A., Courtney, T. K., & Verma, S. K. (2017). Circumstances of fall-related injuries by age and gender among community-dwelling adults in the United States. *PLoS One*, 12.

Wang, T. Y., Bhatt, T., Yang, F., & Pai, Y. C. (2012). Adaptive control reduces trip-induced forward gait instability among young adults. *Journal of Biomechanics, 45*, 1169–1175.

Winter, D. A. (1992). Foot trajectory in human gait - a precise and multifactorial motor control task. *Physical Therapy, 72*, 45–53.

Winter, D. A. (2005). *Biomechanics and motor control of human movement* (3rd ed.). Hoboken, New Jersey: John Wiley & Sons.