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Changes in the symmetry of external perturbations affect patterns of muscle activity during gait initiation

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ABSTRACT

Background: Gait initiation is associated with changes in the steady state and experiencing an external perturbation during initiation of gait could further threaten balance stability.
Research question: The aim of the study was to investigate if changes in the symmetry of the perturbations affect patterns of muscle activity during gait initiation.
Methods: Eleven young health participants were instructed to stand on the force platform and wait for the instruction of taking a right step, left step or stand still while experiencing a pendulum perturbation applied to the back of both shoulders (symmetric), back of the right shoulder (asymmetric) or no perturbations. Bilateral electromyographic activity (EMG) of dorsal and ventral muscles, moments of the pendulum release and perturbation impact, center of pressure (COP) displacements and pelvic movements were recorded and analyzed before and after the onset of the perturbation.
Results: Taking the right/left step in presence of symmetric perturbation did not affect the temporal sequence of COP and pelvic movements. The onset of COP and pelvic movement occurred before the perturbation impact at the shoulder levels. The factors of step and perturbation did not significantly affect integrals of bilateral muscles at the pendulum release. After the pendulum release, ventral and dorsal EMG integrals of the trunk, thigh, and shank segments increased or decreased corresponding to the swing and stance leg. Changes in muscle activities were also associated with the symmetric or asymmetric perturbations before and after the perturbation impact.
Significance: The outcome of the study provides information about strategies used to coordinate the activity of muscles while body perturbations are induced during gait initiation.

1. Introduction

Gait initiation has been well defined as the transient period from the quiet standing posture towards the dynamic steady state walking [1], which challenges older adults' balance control due to changes in the equilibrium status and voluntary limb movement initiations [2]. Both require that the central nervous system (CNS) utilizes pre-designed motor programs to coordinate muscle sequences and contractions during gait initiation. It is classified that changes in the center of pressure (COP) displacements shifting backward and towards to the swing leg until heel off as the anticipatory postural adjustments (APA) phase [2,3]. Meanwhile, inhibition of gastrocnemius muscle and activations of bilateral tibialis anterior muscle were observed in the APA phase of gait initiation [3,4]. This reciprocal and directional-specific muscle activation pattern was also revealed and confirmed as APAs during arm movements [5,6].

When an individual encounters predictable forthcoming perturbations, the CNS employs feedforward [7,8] and feedback mechanisms [9,10] to maintain and restore equilibrium. The feedforward mechanism not only corresponds to the APA phase in gait initiation but also to changes in muscle activation and the COP displacement when having knowledge of external perturbations [11–13]. The lower limb muscles play the postural role in the APA phase and the focal role in transition for the step execution during gait initiation. It has been reported that when the same muscles involved focal (voluntary movement) and postural tasks (external perturbation), the coupling muscles exhibit increased cocontractions and increased muscle activities [6,14]. When the external perturbation from the feet in standing, the shank muscles utilized the reciprocal activation strategy and played as the focal role in postural control. Contrarily, they employed cocontractions for balance maintenance to deal with external perturbations at the shoulders when involved in the postural task [15]. Together, the outcomes of these studies indicate that the CNS precisely coordinates muscle performances to the different point of application of external

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perturbations accordingly. When the upper limbs perform focal tasks, like arm flexion [6] and pushing tasks [16], the lower limb and trunk adjust muscle activities to handle the postural tasks for balance maintenance. Gait initiation is the focal task of the swing leg and the postural task of the stance leg while experiencing asymmetric perturbations involving different postural tasks between the left and right sides of the body. In addition, the combined effects of asymmetric stance and pushing movement have been reported that it resulted in corresponding additive or subtractive postural muscle activities [17]. Deciphering the mechanism of initiating a forward step along with preparing a predictable external perturbation might provide new insights of how the CNS handles the focal task and the postural task at two points of application. Older adults utilized inefficient strategies to control posture when the balance was threatened by the perturbations [18]. The revealed strategies might also benefit to understand impaired coordination of muscle activity, which older adults employed in gait initiation [19].

Thus, the objective of the current study was to investigate how postural muscles of the lower limb and trunk initiate the first step in gait and in response to changes in the symmetry of external perturbations simultaneously. The experimental paradigm involved internal and external body perturbations: the internal perturbation was induced by the lower extremities performing the left or right forward step and the external perturbation was induced by the pendulum impacted at the dorsal surface of shoulders. The first hypothesis was that postural muscles would increase their activity in response to external perturbations compared to the pattern in gait initiation only. Furthermore, the second hypothesis was that left and right muscles would increase or decrease muscle activities corresponding to the left or right step while experiencing either symmetric or asymmetric perturbations.

2. Methods

2.1. Participants

Eleven young volunteers (5 males, 6 females, age = 28.09 ± 4.35 years, height = 1.67 ± 0.07 m, mass = 71.09 ± 18.75 kg) with the right dominant legs participated in the experiment. All participants were free from any musculoskeletal disorder and neurologic disease that could affect performing the experimental tasks. The project was approved by the University of Illinois at Chicago Institutional Review Board, and all participants provided written informed consent before taking part in the experimental procedures.

2.2. Procedure and instrumentation

The participants were instructed to stand still with even body weight distribution between the left and right foot to the best of their effort on a force platform and waited for an experimenter's instruction. A pendulum with a 30 cm long wooden stick and a flag was used to induce perturbations at the shoulders and allowed the participants to see the approaching pendulum via peripheral vision without a need for head rotation (Fig. 1). A load (5% of the individual's body mass: 3.55 ± 0.94 kg) was attached to the pendulum next to its distal end in all the experimental conditions. The pendulum was positioned at an initial angle of 30° to the vertical (0.8 m from the body). After 1 to 2 s the start of each data collection trial, the experimenter would then give the instruction of making a forward step (left or right step) at their self-selected speed on the white straight-line mark or stand still while releasing the pendulum. When making the right step, the right leg was considered as the swing leg while the left leg as the stance leg and vice versa. The distance between the original standing position to the white straight-line mark was adjusted to each individual's step length. In the current study, the condition of the pendulum that impacted both shoulders would be referred to as a symmetric perturbation, while the condition of the impacted the right shoulder would be referred to as an asymmetric perturbation and the condition of no pendulum impacted would be referred to as a non-perturbation. Two practice trials were performed prior to data collection of the nine conditions (1: right step & symmetric perturbation, 2: right step & asymmetric perturbation, 3: right step & non-perturbation, 4: left step & symmetric perturbation, 5: left step & asymmetric perturbation, 6: left step & non-perturbation, 7: stand still & symmetric perturbation, 8: stand still & asymmetric perturbation, and 9: stand still & non-perturbation) and three trials were collected in each condition. The order of the conditions was randomized across participants.

Two accelerometers were used in the experiment. The first accelerometer (model 208CO3, PCB Piezotronics Inc, USA) was attached to the pendulum and its signal was used to determine the timing of the pendulum released and impacted. The experimenter released the pendulum and gave the instruction simultaneously. In the without perturbation conditions, the other experimenter would catch the pendulum right after the pendulum released to avoid it impacting the participants. The second accelerometer (model 1356a16, PCB Piezotronics Inc, USA) was attached to the dorsal surface of the participant at the level of L5/S1 to detect the temporal events of the pelvic movement. Ground reaction forces and moments of forces were recorded using the force platform (Model OR-5, AMTI, USA). EMG of muscles were recorded using disposable surface electrodes (Red Dot, 3 M, USA). After cleaning the skin with alcohol prep pads, electrodes were attached to the bilateral muscle bellies: tibialis anterior (TA), medial gastrocnemius (MG), rectus femoris (RF), biceps femoris (BF), rectus abdominis (RA), and erector spinae (ES). The selected muscles have been used in previous studies of gait initiation [2,20] and anticipatory and compensatory postural adjustments involving externally induced body perturbations [21]. The placement of electrodes was based on recommendations reported in the literature [22] and the interelectrode distance was 2 cm. EMG signals were band-pass filtered (10–500 Hz) and amplified (gain 2000) using the EMG system (Myopac, RUN Technologies, USA). The accelerometer signals, forces, moments of forces, and EMGs were synchronized and digitized with a 16-bit resolution at 1000 Hz by means of an analog-to-digital converter and customized LabVIEW 8.6.1 software (National Instruments, USA).

2.3. Data processing

All data were processed offline using MATLAB software (MathWorks, Natick, MA, USA). The signal from the first accelerometer was used to determine the timing that the pendulum released ($T_{release}$)/the given instruction and impact (T_{impact}). The signal from the second accelerometer signal was used to detect the timing that the pelvic started to move in the up-down ($Pelvic_{X\text{-}onset}$), the left-right ($Pelvic_{Y\text{-}onset}$), and the forward-backward ($Pelvic_{Z\text{-}onset}$) directions. The onsets of the accelerometer signals were detected using the Teager-Kaiser onset time detection method [23]. The ground reaction forces and the moments of forces were filtered with a 20 Hz low-pass, 2nd order, zero-lag Butterworth filter. Time-varying COP traces in the anterior-posterior and medial-lateral directions were calculated using the approximations described in the literature [24]. The onset of the COP moved away from the baseline was detected by the Teager-Kaiser method ($COP_{AP\text{-}onset}$ and $COP_{ML\text{-}onset}$).

All EMG data were high-pass filtered at 20 Hz, full-wave rectified, and low-pass filtered as linear envelope at 2 Hz (2nd order Butterworth) [14]. Subsequently, the Teager-Kaiser method was used to detect the onset of muscle activity for individual muscle (EMG_{onset}). The integrals of EMG activity of all studied muscles (∫EMGs) were calculated during the five periods phase: 1) -150 ~ 50 ms, 2) 50 ~ 250 ms, 3) 250 ~ 450 ms, 4) 450 ~ 650 ms, and 5) 650 ~ 850 ms in relation to $T_{release}$ (0 ms). These selected five phases were according to postural responses to the instruction [25] and postural adjustment evaluations [5,11,26] between the stance and swing legs during gait initiation [27]. Moreover, ∫EMGs of the baseline activity during the 200 ms time window

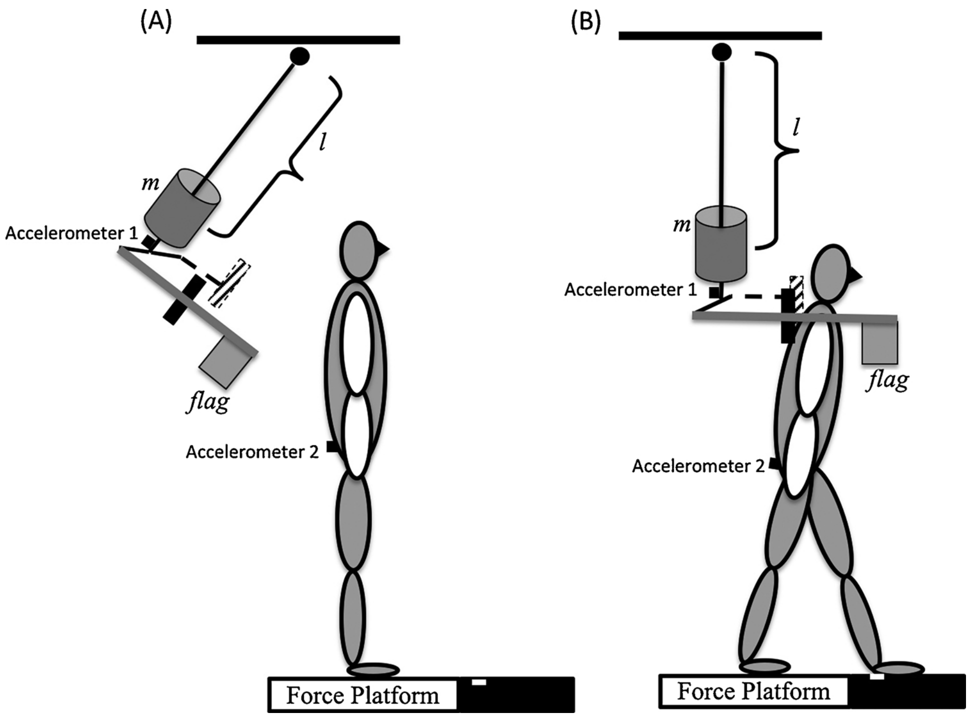

Fig. 1. Schematic representation of the experimental setup. Perturbations were induced by a pendulum impact applied to both shoulders in the symmetric conditions or the right shoulder only in the asymmetric conditions. A white straight-line mark was attached on a black platform, which was the same height as the force platform. *l* – is the adjusted height according to individual shoulder level. m – is the additional weight (5% BW) attached to the pendulum. 1- accelerometer attached to the pendulum, 2- accelerometer attached at the L5S1 level. (A) the original position (B) the end position in the left foot step condition.

Table 1
The results of two-way repeated measure ANOVAs for the duration, $Pelvic_{X\text{-}onset}$, $Pelvic_{Y\text{-}onset}$, $Pelvic_{Z\text{-}onset}$, $COP_{AP\text{-}onset}$ and $COP_{ML\text{-}onset}$.

	Perturbation (P)		Step (S)		P x S	
Duration ($T_{release}$ to T_{impact})	F(1,10)	*p*	F(2,20)	*p*	F(2,20)	*p*
	0.266	0.617	1.494	0.248	3.271	0.059
	F(2,20)	*p*	F(1,10)	*p*	F(2,20)	*p*
$Pelvic_{X\text{-}onset}$	1.365	0.278	0.076	0.788	0.750	0.485
$Pelvic_{Y\text{-}onset}$	0.290	0.752	0.107	0.750	0.300	0.744
$Pelvic_{Z\text{-}onset}$	0.750	0.485	0.082	0.780	0.263	0.771
$COP_{AP\text{-}onset}$	3.403	0.053	3.114	0.108	0.170	0.845
$COP_{ML\text{-}onset}$	3.365	0.055	3.003	0.114	0.587	0.565

(0–200 ms) were obtained at the beginning of the trial. Subtraction of $\int baseline$ was used to eliminate effects of each muscle baseline activity; as a result, activation of muscles was described by values larger than zero ($\int$ EMG > 0) and inhibition by values smaller than zero ($\int$ EMG < 0). Thus, the ∫EMG were normalized by ∫EMGmax, which was the maximum value throughout all experimental trials for each muscle in the six periods, separately as:

$$\int baseline = \int_0^{200} EMG$$

$$\int EMG_{-150\sim50} = \frac{\int_{T_{release}-150}^{T_{release}+50} EMG - \int baseline}{\int EMGmax},$$

$$\int EMG_{50\sim250} = \frac{\int_{T_{release}+50}^{T_{release}+250} EMG - \int baseline}{\int EMGmax}, \text{ and etc.}$$

All variables were calculated for each trial and averaged over three trials.

2.4. Statistics

A two-way repeated measures ANOVA was performed with two factors: step (3 levels: right step, left step, and stand still) and perturbation (2 levels: symmetric and asymmetric) on a duration between $T_{release}$ and T_{impact}. Two-way repeated measures ANOVAs were performed with two factors: step (2 levels: right step and left step) and perturbation (3 levels: symmetric, asymmetric, and non) on temporal variables (EMG_{onset} for individual muscles, $Pelvic_{X\text{-}onset}$, $Pelvic_{Y\text{-}onset}$, $Pelvic_{Z\text{-}onset}$, $COP_{AP\text{-}onset}$ and $COP_{ML\text{-}onset}$). In addition, two-way repeated measures ANOVAs were performed with two factors: step (3 levels: right step, left step, and stand still) and perturbation (3 levels: symmetric, asymmetric, and non) on EMG integrals of five periods for individual muscles. Post hoc comparisons were done using Tukey's Honestly Significant Difference test for significant interactions. The significant difference was set at $p < 0.05$.

3. Results

The duration between $T_{release}$ and T_{impact} was not significantly affected by the factors of perturbation, step, and the interaction (Table 1). The mean duration across six conditions (3 level steps times 2 level perturbations) was 535.90 ± 12.90 ms. In addition, repeated measures ANOVA revealed that $Pelvic_{X\text{-}onset}$, $Pelvic_{Y\text{-}onset}$, $Pelvic_{Z\text{-}onset}$, $COP_{AP\text{-}onset}$ and $COP_{ML\text{-}onset}$ were not significantly affected by the factors of perturbation, step, and the interaction (Table 1). The data averaged across six conditions (2 level steps times 3 level perturbations) and presented in the temporal sequence was that $COP_{AP\text{-}onset}$ at 148.04 ± 9.55 ms and followed by $COP_{ML\text{-}onset}$ at 173.98 ± 11.37 ms, $Pelvic_{X\text{-}onset}$ at 210.30 ± 12.55 ms, $Pelvic_{Z\text{-}onset}$ at 218.39 ± 13.51 ms, and $Pelvic_{Y\text{-}onset}$ at 231.57 ± 15.81 ms in relation to $T_{release}$. Overall, COP and pelvic movement could be classified in the 50 ~ 250 ms phase and T_{impact} occurred in the 450 ~ 650 ms phase.

3.1. Effect of perturbation

Normalized EMG integrals in five 200 ms-time-window from -150 ms to 850 ms in relation to $T_{release}$ were evaluated for each muscle and shown in Table 2. In general, the factor of perturbation did not significantly affect ∫EMG of each muscle in the -150 ~ 50 ms phase. In the 50 ~ 250 ms phase (a pre-anticipatory and partially anticipatory phase in related to T_{impact}), the factor of perturbation significantly

Table 2
The results of two-way repeated measure ANOVAs and pairwise comparisons for EMG integrals of five periods.

	Perturbation					Step				
	F(2,20)	*p*	*S v.s. A*	*S v.s. N*	*A v.s. N*	F(2,20)	*p*	*L v.s R*	*L v.s. n*	*R v.s. n*
−150 ~ 50 ms	0.484	0.624	1.000	1.000	1.000	1.525	0.242	1.000	0.204	1.000
50 ~ 250 ms	8.763	**0.002**	0.545	**0.012**	**0.030**	76.697	**< 0.001**	1.000	**< 0.001**	**< 0.001**
250 ~ 450 ms	5.051	**0.017**	1.000	0.121	**0.009**	96.107	**< 0.001**	0.803	**< 0.001**	**< 0.001**
450 ~ 650 ms	8.010	**0.003**	**0.031**	**0.030**	0.341	31.249	**< 0.001**	1.000	**< 0.001**	**< 0.001**
650 ~ 850 ms	7.722	**0.003**	**0.004**	**0.034**	1.000	42.475	**< 0.001**	**0.017**	**< 0.001**	**< 0.001**
RMG										
−150 ~ 50 ms	2.538	0.105	1.000	0.147	0.125	1.303	0.294	0.184	1.000	1.000
50 ~ 250 ms	2.358	0.120	1.000	0.379	0.247	0.844	0.445	1.000	0.977	1.000
250 ~ 450 ms	14.797	**< 0.001**	0.768	**0.005**	**0.002**	8.459	**0.002**	0.093	1.000	**0.001**
450 ~ 650 ms	17.774	**< 0.001**	**0.033**	**0.001**	**0.032**	3.940	**0.036**	0.308	0.090	1.000
650 ~ 850 ms	18.971	**< 0.001**	0.132	**0.001**	**0.007**	0.924	0.413	0.958	1.000	0.950
RRF										
−150 ~ 50 ms	2.521	0.106	0.269	0.316	1.000	2.192	0.138	1.000	0.377	0.573
50 ~ 250 ms	11.560	**< 0.001**	0.176	**0.005**	**0.011**	47.412	**< 0.001**	1.000	**< 0.001**	**< 0.001**
250 ~ 450 ms	3.976	**0.035**	0.842	0.137	0.174	31.900	**< 0.001**	1.000	**< 0.001**	**< 0.001**
450 ~ 650 ms	23.567	**< 0.001**	0.513	**0.001**	**< 0.001**	46.430	**< 0.001**	**0.007**	**< 0.001**	**< 0.001**
650 ~ 850 ms	19.124	**< 0.001**	0.248	**< 0.001**	**0.017**	25.023	**< 0.001**	0.990	**< 0.001**	**0.001**
RBF										
−150 ~ 50 ms	0.738	0.491	1.000	1.000	0.727	2.918	0.077	1.000	0.101	0.262
50 ~ 250 ms	1.848	0.183	0.908	0.285	1.000	0.182	0.835	1.000	1.000	1.000
250 ~ 450 ms	11.132	**0.001**	0.433	**0.001**	**0.016**	7.210	**0.004**	1.000	0.103	**0.005**
450 ~ 650 ms	18.883	**< 0.001**	**0.043**	**< 0.001**	0.055	7.556	**0.004**	0.095	**0.004**	0.656
650 ~ 850 ms	26.123	**< 0.001**	0.551	**< 0.001**	**0.001**	0.529	0.597	1.000	0.899	1.000
RRA										
−150 ~ 50 ms	2.678	0.093	1.000	0.299	1.000	1.656	0.216	1.000	0.468	0.615
50 ~ 250 ms	1.040	0.372	1.000	0.559	1.000	5.550	**0.012**	1.000	0.141	**0.001**
250 ~ 450 ms	6.488	**0.007**	1.000	**0.043**	**0.030**	24.457	**< 0.001**	0.941	**< 0.001**	**< 0.001**
450 ~ 650 ms	9.015	**0.002**	0.836	**0.008**	**0.018**	34.400	**< 0.001**	1.000	**< 0.001**	**< 0.001**
650 ~ 850 ms	7.124	**0.005**	1.000	**0.049**	**0.024**	14.786	**< 0.001**	1.000	**0.005**	**0.009**
RES										
−150 ~ 50 ms	0.623	0.546	1.000	0.377	1.000	0.087	0.917	1.000	1.000	1.000
50 ~ 250 ms	1.307	0.293	0.916	0.237	1.000	0.119	0.888	1.000	1.000	1.000
250 ~ 450 ms	4.411	**0.026**	1.000	0.077	0.090	6.595	**0.006**	0.245	**0.001**	0.591
450 ~ 650 ms	22.934	**< 0.001**	1.000	**< 0.001**	**0.001**	8.849	**0.002**	0.122	**0.007**	0.246
650 ~ 850 ms	31.126	**< 0.001**	1.000	**< 0.001**	**< 0.001**	0.821	0.454	1.000	1.000	0.428
LTA										
−150 ~ 50 ms	1.547	0.237	1.000	0.578	0.804	0.016	0.984	1.000	1.000	1.000
50 ~ 250 ms	8.085	**0.003**	0.850	**0.016**	0.053	122.139	**< 0.001**	0.035	**< 0.001**	**< 0.001**
250 ~ 450 ms	6.746	**0.006**	1.000	**0.038**	**0.002**	125.213	**< 0.001**	0.635	**< 0.001**	**< 0.001**
450 ~ 650 ms	14.371	**< 0.001**	**0.001**	**0.005**	0.139	88.721	**< 0.001**	1.000	**< 0.001**	**< 0.001**
650 ~ 850 ms	2.652	0.095	1.000	0.209	0.259	26.251	**< 0.001**	0.311	**< 0.001**	**< 0.001**
LMG										
−150 ~ 50 ms	0.864	0.437	1.000	1.000	0.276	2.387	0.118	1.000	0.812	0.111
50 ~ 250 ms	2.481	0.109	0.727	0.137	1.000	1.617	0.223	1.000	1.000	0.073
250 ~ 450 ms	6.158	**0.008**	1.000	**0.036**	**0.021**	15.391	**< 0.001**	1.000	**0.019**	**< 0.001**
450 ~ 650 ms	21.426	**< 0.001**	1.000	**< 0.001**	**0.001**	4.483	**0.025**	1.000	0.151	0.178
650 ~ 850 ms	19.607	**< 0.001**	0.498	**0.001**	**0.002**	3.343	0.056	0.234	0.524	0.180
LRF										
−150 ~ 50 ms	0.626	0.545	1.000	1.000	0.798	1.662	0.215	1.000	0.322	0.939
50 ~ 250 ms	2.061	0.153	1.000	0.317	0.514	56.995	**< 0.001**	1.000	**< 0.001**	**< 0.001**
250 ~ 450 ms	5.365	**0.014**	1.000	0.066	**0.048**	23.308	**< 0.001**	1.000	**< 0.001**	**< 0.001**
450 ~ 650 ms	20.847	**< 0.001**	0.176	**0.001**	**0.001**	31.554	**< 0.001**	0.035	**< 0.001**	**0.001**
650 ~ 850 ms	15.811	**< 0.001**	0.022	**0.002**	**0.042**	28.114	**< 0.001**	0.555	**< 0.001**	**< 0.001**
LBF										
−150 ~ 50 ms	2.530	0.105	0.148	0.217	1.000	1.995	0.168	0.699	0.215	1.000
50 ~ 250 ms	2.224	0.134	0.663	0.138	1.000	1.117	0.347	1.000	1.000	0.697
250 ~ 450 ms	9.905	**0.001**	1.000	**0.011**	**0.015**	2.228	0.134	1.000	0.181	0.323
450 ~ 650 ms	33.891	**< 0.001**	1.000	**< 0.001**	**0.001**	2.615	0.098	0.648	1.000	0.109
650 ~ 850 ms	25.146	**< 0.001**	0.246	**< 0.001**	**0.006**	2.954	0.075	1.000	0.166	0.228
LRA										
−150 ~ 50 ms	2.350	0.121	1.000	0.136	0.506	1.692	0.209	0.087	1.000	0.845
50 ~ 250 ms	1.448	0.259	0.403	0.677	1.000	4.528	**0.024**	1.000	0.164	**0.025**
250 ~ 450 ms	2.269	0.129	1.000	0.148	0.549	11.537	**< 0.001**	1.000	**0.003**	**0.020**
450 ~ 650 ms	3.399	0.054	1.000	0.139	0.051	12.594	**< 0.001**	1.000	**0.002**	**0.009**
650 ~ 850 ms	1.018	0.379	1.000	1.000	0.402	6.629	**0.006**	1.000	**0.001**	0.081
LES										
−150 ~ 50 ms	0.018	0.983	1.000	1.000	1.000	0.413	0.867	1.000	1.000	1.000

(*continued on next page*)

Table 2 (*continued*)

	Perturbation					Step				
	F(2,20)	*p*	*S v.s. A*	*S v.s. N*	*A v.s. N*	F(2,20)	*p*	*L v.s R*	*L v.s. n*	*R v.s. n*
50 ~ 250 ms	1.319	0.290	0.429	0.664	1.000	0.139	0.871	1.000	1.000	1.000
250 ~ 450 ms	3.443	0.052	0.370	0.132	0.685	25.858	< **0.001**	< 0.001	**0.003**	**0.030**
450 ~ 650 ms	43.795	< **0.001**	1.000	< **0.001**	< **0.001**	0.537	0.593	0.882	1.000	1.000
650 ~ 850 ms	30.560	< **0.001**	0.059	< **0.001**	**0.001**	0.654	0.531	0.983	1.000	1.000

F and p values are presented and significant p-values are indicated in bold. L = left, R = right, n = no step (stand still), S = symmetric, A = asymmetric, N = no perturbation, RTA = right tibialis anterior, RMG = right medial gastrocnemius, RRF = right rectus femoris, RBF = right biceps femoris, RRA = right rectus abdominis, RES = right erector spinae, LTA = left tibialis anterior, LMG = left medial gastrocnemius, LRF = left rectus femoris, LBF = left biceps femoris, LRA = left rectus abdominis, and LES = left erector spinae.

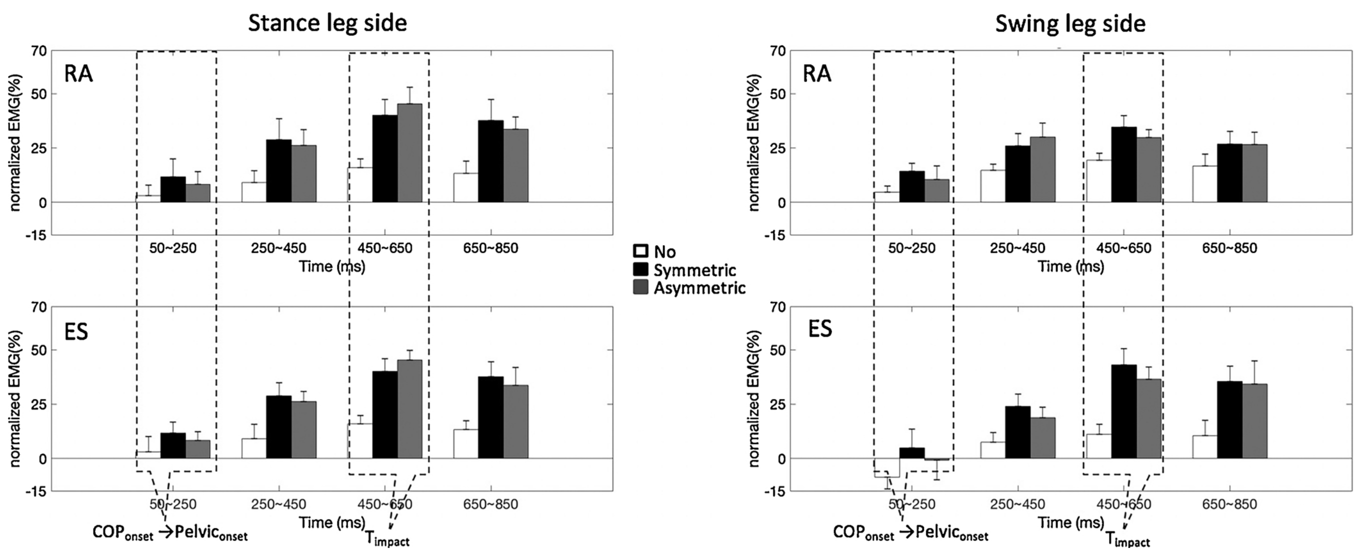

Fig. 2. Normalized EMG integrals for RA (upper panels) and ES (lower panels) muscles on the stance leg side (left) and swing leg side (right) while taking right steps condition during no perturbation (white bars), symmetric perturbations (black bars), and asymmetric perturbations (gray bars) in the four time-period phases. The dash boxes indicate the occurrences of overall COP, Pelvic movement, and the timing of external perturbation impacted.

affected ∫EMG of RTA, RRF, RRA, LTA, and LRA. In the rest phases (250 ~ 850 ms), the factor of perturbation significantly affected ∫EMG of bilateral muscles, except effects of perturbations on LRA in the 650 ~ 850 ms phase.

Normalized EMG integrals of ventral and dorsal muscles of the trunk (Fig. 2), thigh (Fig. 3), and shank (Fig. 4) segments were illustrated in the no-perturbation, symmetric, and asymmetric perturbation while taking the right step. For the trunk segment, increased ∫EMG of bilateral

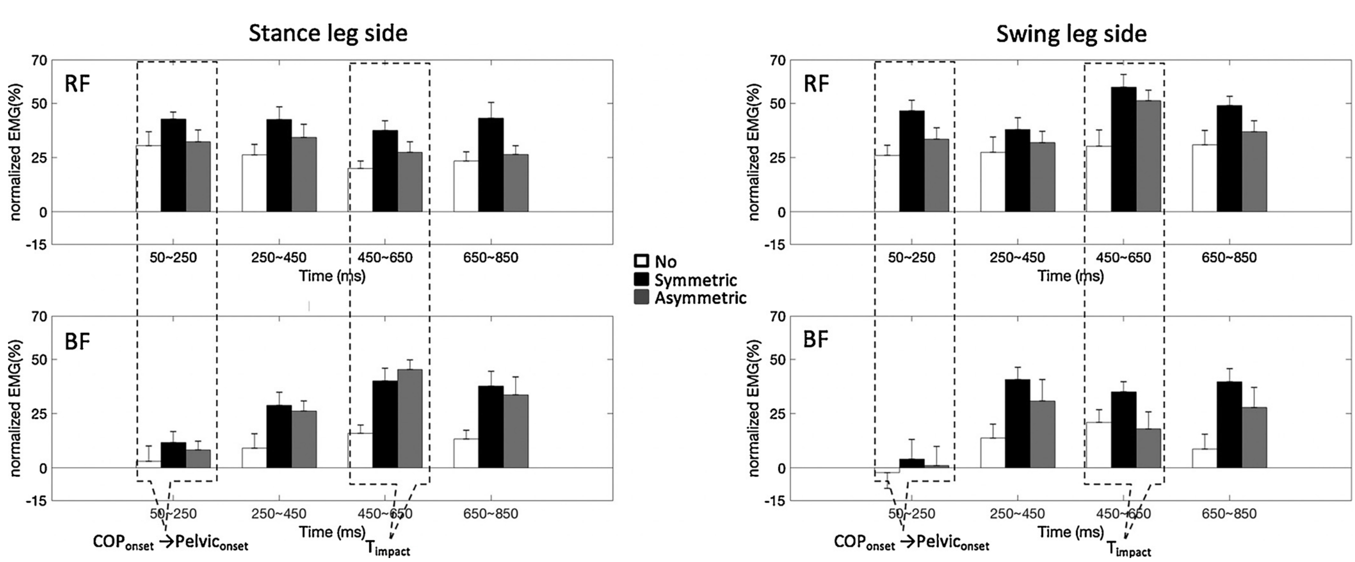

Fig. 3. Normalized EMG integrals for RF (upper panels) and BF (lower panels) muscles on the stance leg side (left) and swing leg side (right) while taking right steps condition during no perturbation (white bars), symmetric perturbations (black bars), and asymmetric perturbations (gray bars) in the four time-period phases. The dash boxes indicate the occurrences of overall COP, Pelvic movement, and the timing of external perturbation impacted.

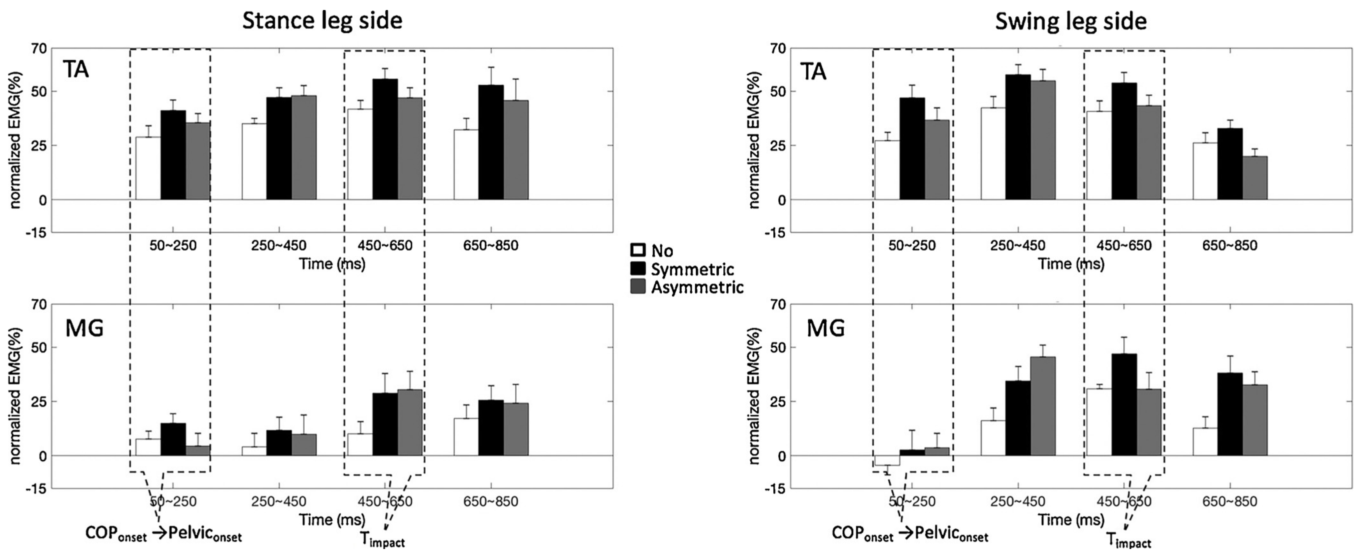

Fig. 4. Normalized EMG integrals for TA (upper panels) and MG (lower panels) muscles on the stance leg side (left) and swing leg side (right) while taking right steps condition during no perturbation (white bars), symmetric perturbations (black bars), and asymmetric perturbations (gray bars) in the four time-period phases. The dash boxes indicate the occurrences of overall COP, Pelvic movement, and the timing of external perturbation impacted.

RA and ES were observed from the 250 ~ 450 ms phase, particularly the left muscles in the asymmetric perturbation. Furthermore, thigh segment showed larger ∫EMG of RF on the swing leg and BF on the stance leg and smaller ∫EMG of BF on the swing leg and RF on the stance leg in the asymmetric perturbation (Fig. 3). In addition, larger ∫EMG of bilateral RF and BF were observed in the symmetric perturbation conditions. Increases ∫EMG in of bilateral TA were observed and MG on the swing leg (MG on the stance leg) showed related larger (smaller) normalized integrals from the 250 ~ 450 ms phase in Fig. 4. Also, RMG showed opposite patterns in the symmetric and asymmetric perturbation conditions in the 250–450 ms and 450–650 ms phases. After the perturbation impacted, remained large ∫EMG of bilateral trunk and thigh segments while decreased ∫EMG of TA on the swing leg were observed in the 650–850 ms phase.

3.2. Effect of side

The factor of step did not significantly affect ∫EMG of each muscle in the −150–50 ms phase. In the rest phases (250–850 ms), ∫EMG of bilateral ventral muscles were significantly affected by the factor of side (Table 2). For dorsal muscles, the factor of step significantly affected ∫EMG of RMG, RBF, RES, and LMG in the 250–450 ms and 450 ~ 650 ms phases as well as LES in the 250–450 ms phase. Lastly, the similar patterns of ∫EMG (Figs. 2–4) exchanged between the swing (left) and stance (right) legs were observed in the left-step condition while experiencing to the symmetric perturbation.

4. Discussion

The current study was conducted to investigate how changes in the symmetry of external perturbations affect the muscle activities during the left or right step in gait initiation. The duration between $T_{release}$ and T_{impact} and other temporal variables, $COP_{AP\text{-}onset}$, $COP_{ML\text{-}onset}$, $Pelvic_{X\text{-}onset}$, $Pelvic_{Z\text{-}onset}$, and $Pelvic_{Y\text{-}onset}$ were not different across conditions. After the COP onset, increased ∫EMG of most muscles were significantly larger in the with perturbations condition than the without perturbation condition as well as in the step condition compared to the stand still condition.

In the -150 ~ 50 ms phase, all normalized EMG integrals were not affected by the factors of step and perturbation which indicated that participants did not make any expectation and guess until the given instruction. After the given instruction (0 ms), pelvic movement represented the center of mass (COM) and moved after COP was in line with the previous lectures [1,3], which were occurred in the 50 ~ 250 ms phase. Meanwhile, it included both the pre-anticipatory and partially anticipatory phase [2], which demonstrated increases in bilateral TA and RF muscle activities in the step conditions [1,3,27]. In addition, the larger muscle activities in the perturbations condition than the non-perturbation condition suggested that participants activated additional muscle activities to prepare the forthcoming perturbation as soon as knowing its occurrence.

4.1. Effect of perturbation

The duration between the COP onset and the external perturbation was around 400 ms, which indicated that the instant of the external perturbation impacted at the shoulders was before heel-off [3,27] and occurred in the 450 ~ 650 ms phase. Hence, this phase and the previous (250–450 ms) phase could be considered as anticipatory and early postural adjustments respectively (within the APA phase of gait initiation), which have been identified when experienced to the predictable perturbations [13]. However, the symmetric and asymmetric perturbations at the shoulder level did not affect muscle activation patterns of the shank segments during gait initiation. Postural muscles of trunk and shank segments reacted to the perturbation at the shoulders and gait initiation, correspondingly. It was supported by effects of perturbations at different point of application [15].

After the perturbation impact (the 650 ~ 850 ms phase), the trunk segment remained substantial muscle activities to compensate for the instability induced by the external perturbation [6,15]. Meanwhile, reciprocal muscle activity of the swing leg and cocontraction of the stance leg were observed on the shank segments. It was in response to perturbations of body weight shifting from the swing leg to the stance leg in gait initiation [1,2]. The similar patterns were observed in the thigh segment. It implies that the external perturbation did threaten balance stability in the transient period from the quiet standing posture towards the dynamic steady state walking, particularly in the period of unloading and loading legs [2]. In addition, three different roles of three segments indicated that the CNS fine tune muscle coordination accordingly [28,29] supports the hypothesis that gait initiation in presence of symmetric perturbation affects patterns of muscle activity in healthy adults. However, older adults or individuals with Parkinson's disease fail to initiate a step due to impaired coordination of muscle activity [19]. Given the fact that all different rehabilitation interventions are not always effective in resolving freezing of gait in individuals with Parkinson's disease, future studies of external perturbations (push) during gait initiation in individuals with Parkinson's disease are needed.

4.2. Effect of side

Taking a left or right step did not affect the magnitudes of bilateral trunk muscle activities. Right trunk muscles were smaller in the asymmetric perturbations compared to left trunk muscles, which remained substantial muscle activities in the symmetric and asymmetric perturbations conditions. The comparable effects were reported on postural adjustments when one hand pushed in asymmetric stance [17,30] and holding an object with symmetric perturbations [29]. In addition, thigh segment showed more strategic patterns to handle symmetric and asymmetric perturbations and prepare left/right step simultaneously. When taking the right step (Fig. 3), the CNS utilized the opposite pattern between the swing (RF ↑and BF↓) and stance (RF ↓ and BF↑) legs with asymmetric perturbation, but co-contraction muscle patterns of the stance leg with symmetric perturbations. It also confirmed the role of thigh segment encountering external perturbations involved changes in the symmetry of perturbations [15,31].

The reciprocal and co-contraction activation patterns of the shank segment were corresponding to the swing and stance legs. During these phases (250–450 ms and 450–650 ms) in general gait initiation, COP was supposed moving from the swing leg towards the stance leg [1,3,27] and both dorsal muscles showed silencing with large ventral muscle activities [1,20]. However, the perturbations did cause larger muscle activities of bilateral TA and MG of the swing leg. It suggests that the CNS might stall shifting COP and enhance stiffness with co-contraction to prioritize stability before limb movement [2,18]. Nevertheless, the healthy individuals were able to increase corresponding muscle activity to prepare gait initiation and maintain balance successfully.

4.3. Limitations

The study has some limitations. First, only one force platform was used in the current experiment which resulted in changes in the COP displacement could not be calculated after left or right foot landing on the white straight-line mark. Second, the exact timing of foot movement could not be detected due to no accelerometers or markers attached to the feet. Thus, we only utilized the onset of COP along with pelvic movement to compare with the previous lectures and establish the temporal event in the current study.

5. Conclusions

Changes in the symmetry of perturbations and taking left or right step did not affect the chronological sequence of COP and pelvic movement in gait initiation while awareness of the predictable perturbation. Subsequently, the trunk segment co-contracted the bilateral ventral and dorsal muscles in experiencing the symmetric perturbation or ipsilateral at the impact side of the asymmetric perturbation. Muscle activation patterns of bilateral thigh segments were affected by the external perturbation and step side simultaneously. For the shank segment, co-contracting muscles of the swing leg were used to stall COP shifting towards to the stance leg. The outcome of the current study highlights that the CNS coordinated three segments and left/right side of the body separately to utilize corresponding strategies for stability prioritization and when developing rehabilitation regimens for individuals with gait initiation problem.

Conflict of interest

The author declare that no financial and personal relationships with other people or organisations have inappropriately influenced the content of the work reported in this paper.

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References

[1] E. Yiou, T. Caderby, A. Delafontaine, P. Fourcade, J.L. Honeine, Balance control during gait initiation: state-of-the-art and research perspectives, World J. Orthop. 8 (2017) 815–828.
[2] R. Khanmohammadi, S. Talebian, M.R. Hadian, G. Olyaei, H. Bagheri, Characteristic muscle activity patterns during gait initiation in the healthy younger and older adults, Gait Posture 43 (2016) 148–153.
[3] J.L. Honeine, M. Schieppati, O. Crisafulli, M.C. Do, The neuro-mechanical processes that underlie goal-directed medio-lateral APA during gait initiation, Front. Hum. Neurosci. 10 (2016) 445.
[4] M. Ko, M.D. Bishop, A.L. Behrman, Effects of limb loading on gait initiation in persons with moderate hemiparesis, Top. Stroke Rehabil. 18 (2011) 258–268.
[5] A.S. Aruin, M.L. Latash, Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements, Exp. Brain Res. 103 (1995) 323–332.
[6] B. Chen, Y.J. Lee, A.S. Aruin, Standing on a sliding board affects generation of anticipatory and compensatory postural adjustments, J. Electromyogr. Kinesiol. 38 (2018) 168–174.
[7] P. Hodges, A. Cresswell, A. Thorstensson, Preparatory trunk motion accompanies rapid upper limb movement, Exp. Brain Res. 124 (1999) 69–79.
[8] J.A. Leonard, R.H. Brown, P.J. Stapley, Reaching to multiple targets when standing: the spatial organization of feedforward postural adjustments, J. Neurophysiol. 101 (2009) 2120–2133.
[9] C.R. Lowrey, J.Y. Nashed, S.H. Scott, Rapid and flexible whole body postural responses are evoked from perturbations to the upper limb during goal-directed reaching, J. Neurophysiol. 117 (2017) 1070–1083.
[10] M. Desmurget, S. Grafton, Forward modeling allows feedback control for fast reaching movements, Trends Cogn. Sci. (Regul. Ed.) 4 (2000) 423–431.
[11] A.S. Aruin, N. Kanekar, Y.J. Lee, Anticipatory and compensatory postural adjustments in individuals with multiple sclerosis in response to external perturbations, Neurosci. Lett. 591 (2015) 182–186.
[12] N. Kanekar, A.S. Aruin, Aging and balance control in response to external perturbations: role of anticipatory and compensatory postural mechanisms, Age (Dordr). 36 (2014) 9621.
[13] V. Krishnan, A.S. Aruin, Postural control in response to a perturbation: role of vision and additional support, Exp. Brain Res. 212 (2011) 385–397.
[14] Y.J. Lee, M.J. Hoozemans, J.H. van Dieen, Oblique abdominal muscle activity in response to external perturbations when pushing a cart, J. Biomech. 43 (2010) 1364–1372.
[15] B. Chen, Y.J. Lee, A.S. Aruin, Role of point of application of perturbation in control of vertical posture, Exp. Brain Res. 235 (2017) 3449–3457.
[16] Y.J. Lee, B. Chen, J.N. Liang, A.S. Aruin, Control of vertical posture while standing on a sliding board and pushing an object, Exp. Brain Res. 236 (2018) 721–731.
[17] Y.J. Lee, A.S. Aruin, Isolated and combined effects of asymmetric stance and pushing movement on the anticipatory and compensatory postural control, Clin. Neurophysiol. 125 (2014) 768–776.
[18] Y.J. Lee, B. Chen, A.S. Aruin, Older adults utilize less efficient postural control when performing pushing task, J. Electromyogr. Kinesiol. 25 (2015) 966–972.
[19] C.J. Hass, D.E. Waddell, S.L. Wolf, J.L. Juncos, R.J. Gregor, Gait initation in older adults with postural instability, Clin Biomech (Bristol, Avon) 23 (2008) 743–753.
[20] J.V. Jacobs, J.G. Nutt, P. Carlson-Kuhta, M. Stephens, F.B. Horak, Knee trembling during freezing of gait represents multiple anticipatory postural adjustments, Exp. Neurol. 215 (2009) 334–341.
[21] R. Claudino, E.C. dos Santos, M.J. Santos, Compensatory but not anticipatory adjustments are altered in older adults during lateral postural perturbations, Clin. Neurophysiol. 124 (2013) 1628–1637.
[22] J.V. Basmajian, Electromyography–dynamic gross anatomy: a review, Am. J. Anat. 159 (1980) 245–260.
[23] X. Li, P. Zhou, A.S. Aruin, Teager-Kaiser energy operation of surface EMG improves muscle activity onset detection, Ann. Biomed. Eng. 35 (2007) 1532–1538.
[24] D.A. Winter, F. Prince, J.S. Frank, C. Powell, K.F. Zabjek, Unified theory regarding A/P and M/L balance in quiet stance, J. Neurophysiol. 75 (1996) 2334–2343.
[25] M.W. Rogers, C.G. Kukulka, D. Brunt, T.D. Cain, T.A. Hanke, The influence of stimulus cue on the initiation of stepping in yound and older adults, Arch. Phys. Med. Rehabil. 82 (2001) 619–624.
[26] A.S. Aruin, M.L. Latash, The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations, Exp. Brain Res. 106 (1995) 291–300.

[27] K. Hiraoka, R. Hatanaka, Y. Nikaido, Y. Jono, Y. Nomura, K. Tani, et al., Asymmetry of anticipatory postural adjustment during gait initiation, J. Hum. Kinet. 42 (2014) 7–14.
[28] B. Chen, Y.J. Lee, A.S. Aruin, Anticipatory and compensatory postural adjustments in conditions of body asymmetry induced by holding an object, Exp. Brain Res. 233 (2015) 3087–3096.
[29] B. Chen, Y.J. Lee, A.S. Aruin, Control of grip force and vertical posture while holding an object and being perturbed, Exp. Brain Res. 234 (2016) 3193–3201.
[30] Y.J. Lee, A.S. Aruin, Effects of asymmetrical stance and movement on body rotation in pushing, J. Biomech. 48 (2015) 283–289.
[31] Y.J. Lee, J.N. Liang, B. Chen, M. Ganesan, A.S. Aruin, Standing on wedges modifies side-specific postural control in the presence of lateral external perturbations, J. Electromyogr. Kinesiol. 36 (2017) 16–24.