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Effect of cue timing and modality on gait initiation in Parkinson's disease with freezing of gait

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Abstract

Objective—To examine the effects of cue timing, across three sensory modalities, on anticipatory postural adjustments (APAs) during gait initiation in people with Parkinson's disease (PD).

Design—Observational study.

Setting—Biomechanics research laboratory.

Participants—Twenty-five individuals with idiopathic PD (11 with freezing of gait, FOG) were studied in the off-levodopa state (12-hour overnight withdrawal).

Interventions—Gait initiation was tested without cueing (self-initiated) and with three cue timing protocols: fixed delay (3 s), random delay (4–12 s) and countdown (3-2-1-go, 1 s intervals) across three sensory modalities (acoustic, visual and vibrotactile).

Main Outcome Measures—The incidence and spatiotemporal characteristics of APAs during gait initiation were analyzed, including vertical ground reaction forces and center of pressure.

Results—All cue timings and modalities increased the incidence and amplitude of APAs compared to self-initiated stepping. Acoustic and visual cues, but not vibrotactile stimulation, improved the timing of APAs. Fixed delay or countdown timing protocols were more effective at decreasing APA durations compared to random delay cues. Cue-evoked improvements in APA timing, but not amplitude, correlated with the level of impairment during self-initiated gait. Cues did not improve the late push-off phase in the FOG group.

Conclusions—External cueing improves gait initiation in PD regardless of cue timing, modality, or clinical phenotype (with and without FOG). Acoustic or visual cueing with predictive timing provided the greatest improvements in gait initiation thus these protocols may provide the best outcomes when applied by caregivers or devices.

Keywords

Cueing; Gait initiation; Parkinson's disease; Freezing; Anticipatory postural adjustments

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Gait initiation is normally preceded and accompanied by a sequence of anticipatory postural adjustments (APAs) which stabilize posture to allow the stepping leg off the ground. APAs accelerate the center of mass forward and toward the initial stance limb, typically by shifting the net center of pressure (CoP) backward and toward the stepping leg while the initial stepping and stance legs respectively load and unload.^{1–3} People with Parkinson's disease (PD) often self-initiate gait without APAs or with reduced amplitude and longer duration.^{4–6} Impaired APAs are associated with decreased initial gait velocity, a shortened step and an increased fall risk.^{7,8}

External sensory cues are commonly used to facilitate gait initiation in people with PD,^{5,9,10} particularly for those with freezing of gait (FOG).⁹ During FOG, movement is arrested and the individual feels that their feet are “glued to the floor”. There are no clinical guidelines for optimal cue presentation and cueing effects on gait initiation have been equivocal. Acoustic or somatosensory cues, presented at a pseudo-random time intervals, improved the amplitude and timing of APAs.^{5,11} A single visual cue improved APAs, but attenuated the first step length.¹² Neither rhythmic acoustic or visual cues significantly improved APA timing or magnitude, but visual cues increased the first stride length.¹³ Stimulus modality and timing affect APA timing and/or magnitude, but it is unclear how (modality) and when (timing) to present cues for optimal gait initiation.

Effects of cue timing on gait initiation in people with PD have not been studied. In healthy adults, motor cortical preparatory activity increases gradually between a warning and go cue when the timing of the imperative stimulus can be anticipated.^{14–19} Conversely, when the timing is not predictable, movement-related activity begins after the go cue.²⁰ Individuals with PD retain the capacity to prepare APAs in advance of a temporally predictable cue.¹⁰ If early preparatory cortical activity contributes to the effectiveness of external cueing, then protocols using temporally predictive cues should be superior to reactive cueing protocols.

The main purpose of this study was to examine the effects of external cue timing on the timing, magnitude and incidence of APAs. We also examined if effects differed across acoustic, visual, or somatosensory modalities. The three timing protocols, differing in predictability of the imperative “go” cue, were designed to be analogous to common clinical strategies (e.g. countdown: “three, two, one, go”; fixed delay: “get ready – go”; random delay: “get ready... go”). We hypothesized that: 1) the anticipatory timing protocols (fixed delay and countdown) would significantly improve the amplitude and timing of the APA sequence and decrease the incidence of incomplete APAs compared with reactive cues (random delay) and self-initiated stepping, and 2) the cueing effects would be greater in people with PD and FOG compared to PD without FOG. We further explored if the effects of cue timing differed across sensory modalities.

Methods

Participants

Twenty-five participants diagnosed with idiopathic PD were tested. The sample size was based on studies that compared gait initiation between cued and self-initiated conditions in

people with PD^{5,10,13} (estimated effect size for vertical ground reaction forces = $5 \pm 5\%$ body weight, $P = 0.05$, power = 90%). Eleven participants had FOG (PD+FOG) (mean $\pm$ SD, age = 66.3 ± 1.6 yrs; 7 men) and 14 did not (PD-FOG) (64.3 ± 9.1 yrs; 9 men). The presence of FOG was classified based on their response to question 1 of the New FOG Questionnaire²¹ and direct observation of an FOG episode during a clinical or laboratory visit. For the PD+FOG group, the average score for the FOG questionnaire was 19.3 ± 6.6 , disease duration was 7.8 ± 3.4 years, “OFF medications” Unified Parkinson’s Disease Rating Scale (UPDRS) part III score was 30.7 ± 8.0 , Montreal Cognitive Assessment (MoCA) score was 25.6 ± 2.7 , and levodopa equivalent dosage was 1059.8 ± 395.8 mg. For the PD-FOG group, disease duration was 4.7 ± 3.4 years, UPDRS part III score was 29.0 ± 11.5 , MoCA score was 26.8 ± 2.6 , and the levodopa equivalent dosage was 580.8 ± 434.8 mg. Participants were tested in the morning after overnight withdrawal (12+ hours) from antiparkinson’s medications. Participants were excluded for a musculoskeletal disorder affecting lower limb movement, a tremor score greater than 2 on items 20 and 21 of the UPDRS, clinically significant reductions in vision or hearing (when corrected), diagnosis of peripheral neuropathy in lower limbs, and dementia or a score of less than 24 on the MoCA. Written informed consent was obtained and the Institutional Review Board at the University of Minnesota approved all procedures.

Protocol

Participants stood on two force platforms^a in their natural stance. Each foot was outlined to ensure a consistent initial position across trials. Gait initiation was cued using three timing protocols (Figure 1A): 1) fixed delay (a warning cue followed 3 s later by a go cue), 2) countdown (3 warning cues followed by the go cue, 1 s between each cue; akin to “3 – 2 – 1 – go”) and 3) random delay (a warning cue followed 4 – 12 s later by the go cue). The fixed delay and countdown protocols were derived from anticipatory timing studies showing preparatory movement-related cortical activity increases during the interval between the warning and go cues.^{14–19} The random delay interval was selected to minimize temporal anticipation and ensure that subjects initiated movement in reaction to the “go” cue.^{14–19} Three sensory modalities were used: acoustic, visual and vibrotactile. For the acoustic and visual modalities, cues were presented with a speaker^b or a vertical array of light emitting diodes^c placed at eye level, 3 m in front of the participants. The acoustic warning tone was 80 dB and 1000 Hz and the go tone was 90dB and 2000 Hz (each 100 ms). The visual warning and go cues were yellow and green respectively (each 100 ms). For the vibrotactile modality, a vibrotactile transducer^d was attached to the lateral malleolus of the initial stance leg (diameter 2.03 cm, weight 8 g, 250 Hz for 100 ms, maximum power output, 0.1 cm peak displacement). Stimulating this dermatome region is associated with a withdrawal reflex-like response (activation of tibialis anterior and suppression of soleus).^{22,23} It was hypothesized that the vibrotactile stimulus would facilitate the initial unloading of the stance limb characteristic of an appropriate APA.

^aForce plates: Kistler, 75 John Glenn Drive, Amherst, NY 14228-2171 USA

^bSpeaker: Atlas sound, 1601 Jack Mckay Blvd, Ennis, Texas 75119 USA

^cLight emitting diodes: CREE, 4600 Silicon Drive, Durham, North Carolina 27003 USA

^dVibrotactile transducer: C3 Tactor, Engineering acoustics Inc, 406 Live Oaks Blvd, Casselberry, FL 32707, USA

Participants were told that a warning cue would be followed by a go cue and to “hold still and wait for the go cue” before initiating three or more steps forward “as fast as possible” starting with their preferred stepping leg. Participants also performed a set of self-initiated (un-cued) trials during which they initiated stepping “as fast as possible”, after waiting a minimum of 3 to 5 s following the verbal instruction of “Anytime” (Figure 1A). Self-initiated trials were repeated if the participant initiated the step in reaction to the verbal instruction. Cued trials were collected in 9 randomized blocks of 6 trials for each cue timing-modality condition. Twelve self-initiated trials were collected in 2 blocks (1 block at the beginning and end of the data collection session).

Data analysis

The primary outcome variables focused on the timing and amplitudes of the primary kinetic components of the APA and the incidence of trials in which medial-lateral or anterior-posterior components of the APA were absent. A complete APA sequence was defined based on the presence of: 1) an initial backward excursion of the CoP (CoPap1), 2) an initial lateral excursion of the CoP toward the stepping leg (CoPml), 3) increased vertical ground reaction forces (GRF) (loading) of the initial stepping leg, and 4) decreased vertical GRF (unloading) of the initial stance leg. A trial missing one or more components was considered an incomplete APA trial. For each trial, APA amplitudes and times (from weight shift onset to the event) were computed for (Figure 1B): peak step leg loading force, peak stance leg unloading force, peak posterior excursion of the CoP during loading/unloading (CoPap1) and near step leg toe-off (CoPap2), and peak lateral excursion toward the step leg (CoPml). The times from weight shift onset to step and stance leg toe-off and the reaction times from cue onset to initial change in step leg loading force (cued conditions only) were also analyzed. Forces were normalized to a percentage of total body weight (BW). CoP movement and force onsets were identified when the signal crossed a threshold of ± 3 standard deviations from baseline quiet standing, verified, and adjusted by visual inspection.

Statistical analyses

Since the psychophysical intensities of the stimulation modalities were not matched within-subjects, the effects of cue timing on APAs during gait initiation were analyzed separately for each cue modality, using a 2 x 4 repeated measures analysis of variance (ANOVA) to test for differences between groups (PD+FOG vs. PD-FOG) and cue timing conditions (self-initiated, fixed delay, random delay, and countdown). Reaction times were tested with a 2 x 3 repeated measures ANOVA for the effects of group and cue timing (excluding self-initiated). Greenhouse-Geisser corrected degrees of freedom were used to correct for violations of the assumption of sphericity. The incidence of incomplete APAs was analyzed with a generalized estimating equation regression analysis with repeated measures for the effects of group and cue timing. The change in performance between the self-initiated and cued conditions was calculated by subtracting the self-initiated from each cue timing condition in each individual. Relationships between APAs in the self-initiated trials and the changes in performance with a cue were examined using Pearson correlation coefficients. Bonferroni corrections were applied for multiple comparisons with two-tailed adjusted *P* values set at 0.05.

Results

Complete data sets were captured in 20 of 25 participants. One participant (PD+FOG) did not complete the visual and vibrotactile conditions due to fatigue and 4 participants (3 PD +FOG) did not complete the vibrotactile condition due to an inability to reliably detect the stimulus. No significant difference was found between the first and the last self-initiated blocks in both groups, so the self-initiated trials were pooled for analysis.

Effect of cueing on the incidence of APAs

Cueing markedly reduced the incidence of incomplete APAs compared to self-initiated gait. Sixteen participants exhibited at least one incomplete APA sequence. APAs were incomplete (one or more components missing) in 16% of self-initiated trials. The predominant pattern had all four APA components absent and occurred in 6% of self-initiated trials. Incomplete APAs were only present in 1% of all cued trials. A significant main effect of cue timing on the incidence of APAs existed for all modalities (acoustic, visual and vibrotactile, $P < .001$; Table 1). Acoustic and visual cues significantly decreased the incidence of incomplete APAs compared with the self-initiated condition across all three cue timings. The post-hoc analysis in cue timing for vibrotactile cue failed to reach significance ($P > .078$). There were no main effects of group or group x condition interactions for all cue modalities.

Effects of cueing on APA amplitude

All cue conditions significantly increased the magnitude of APAs relative to self-initiated stepping (main effect, $P < .004$) (Figure 2A, Table 2, Table 3). Acoustic and visual cueing improved the amplitude of the initial loading and unloading forces by an average of 60% and CoP excursions by 52%. Improvements with vibrotactile cueing were slightly less (40% for loading and unloading, 31% for CoP excursions). There was no effect of cue timing on APA amplitudes for any modality. An interaction between group and cue timing was observed for the peak CoPap2 in all modalities. Post-hoc testing showed that the peak CoPap2 was significantly increased by all cueing modalities in the PD-FOG group but not in the PD +FOG group. This finding shows that cueing was effective in improving forward propulsion late in the push-off phase of gait initiation (near toe-off) in participants without FOG, but not those with FOG.

Temporal characteristics of gait initiation

Acoustic and visual cues significantly reduced APA durations compared to the self-initiated condition (main effect, $P < .004$). The time to peak loading and unloading were reduced by an average of 19% and the time to the CoP peaks by an average of 15%. Trials with randomly delayed cues had longer APA durations than the fixed delay and countdown conditions. Vibrotactile cues had no significant effect on APA timing, but decreased the time to stance leg toe-off in the count down condition, compared to both the self-initiated ($P = .001$) and random delay ($P = .041$) conditions. There were no main effects on APA timing for FOG group or interactions between group and condition.

Self-initiated APA duration predicts cue-induced improvement in APA timing

The change in APA duration was negatively correlated with APA duration during the self-initiated condition for the acoustic ($R^2 = .37$ to $.75$) and visual ($R^2 = .65$ to $.87$) modalities. In other words, participants with prolonged self-initiated APA durations showed the greatest reductions in APA duration with an acoustic or visual cue. Correlations were weak or not significant for the APA amplitude variables for the acoustic ($R^2 = .10$ to $.49$) and visual ($R^2 = .04$ to $.42$) modalities. In the vibrotactile cueing condition, the correlation was weak or not significant for both APA timing ($R^2 = .01$ to $.52$) and amplitude ($R^2 = .02$ to $.32$) variables (see Supplemental Table 1).

Discussion

External cueing significantly improved the timing and amplitude of APAs during gait initiation and reduced the incidence of incomplete or absent APAs across cue timings and modalities. These effects were most pronounced using acoustic or visual cues with predictable cue timings.

Fixed delay and countdown conditions significantly improved the timing of the APA and the propulsive phase of gait initiation, but randomly delayed cues produced longer APA durations than the other cue timings, and did not significantly improve timing relative to the self-initiated condition for many variables. Rhythmic acoustic tones or static visual cues previously did not improve gait initiation timing, but random-delay acoustic or somatosensory cues improved APA timing.^{5,11,12} Those studies differed from our experiment with respect to medication state,¹² the presence of deep brain stimulation¹¹ and method of cue presentation. Differences in the severity of gait initiation impairment may also explain discrepancies across studies. We showed that participants with the longest APA durations during self-initiated gait benefited the most from external cueing. The average disease severity of the subjects in previous studies^{5,11} was greater than our cohort, which may have enhanced the effects of random cues. Nonetheless, our data suggest that fixed delay and countdown strategies are more effective than random cues for improving gait initiation timing.

The feature differentiating the countdown and fixed delay protocols from the random delay condition was the predictability of the go cue. Temporally predictive cues allow the APA to be prepared in advance of the imperative go cue.²⁴ The long interval in the random delay condition (4–12s) was designed to minimize preparatory cortical activity^{19,25} and ensure a reactive response to the go cue. The attentional demands for long delays were likely high, which may have increased reaction times and lessened the cueing effects. Nonetheless, our results show that protocols requiring a reactive response are not as effective as anticipatory timing protocols.

Cues improved the amplitude of forces and CoP shifts during the APA,⁵ but deficits in APA amplitude during the self-initiated condition were not correlated with the improvement evoked by cueing. While participants with the lowest forces during self-initiated gait impairment tended to improve the most (Figure 2B), participants with relatively normal force generation also improved with a cue.

Cueing effects on APA timing varied across modalities. Visual and acoustic cues reduced APA and toe-off timings for all cue-timing conditions, particularly for the fixed delay and countdown strategies. The effects of the vibrotactile cue were inconsistent within and across participants, had no significant effect on APA timing, significantly reduced toe-off timing for only the countdown timing condition and had reduced efficacy on APA amplitude than the acoustic and visual cues. The reduced effectiveness of vibrotactile stimulation compared with studies that used electrical or mechanical stimuli more proximally,^{5,12} might be explained by the mechanical delivery, lower intensity, or distal application site. We anticipated that stimulation of the lateral malleolus of the initial stance limb would reinforce the APA sequence in a manner similar to studies that provided postural assistance via sural nerve stimulation,²⁶ floor vibration, or a support surface drop of the stance limb.^{27,28} Our findings illustrate the challenges of using a cutaneous or proprioceptive sensory cue in a population that often has compromised sensation due to ageing, parkinsonism and additional neurological complications.^{29,30} Though impairments in vision and hearing can also reduce effectiveness of external cueing, all modalities showed improvement relative to self-initiated stepping. As four participants were unable to sense the maximal vibration, we suggest that selection of cue modality should be individualized with stimulus intensity tailored to individual perceptual threshold.

APAs did not differ between people with and without FOG, except for the absence of a cue-evoked improvement in the second posterior excursion peak in CoP in the PD+FOG group. CoPap2 is in the step execution phase and accelerates the center of mass forward.^{5,11,31} Previous studies have also shown deficits in step execution in people with FOG.^{11,32} Therefore, impaired APAs are common to PD, with FOG causing additional deficits during step execution (push-off and first step).

Study Limitations

Our results are only interpretable for laboratory settings with novel cues and acute exposure. Cueing protocols tested in this study may not be effective over the long term or in other environments. Fatigue and practice may have affected later performance, but as the self-initiated blocks bookending the experiment showed no change, the effects of these confounds are probably negligible.

Conclusions

Our findings demonstrate that anticipatory timing protocols (fixed delay or countdown) with acoustic or visual stimuli provide effective facilitation of gait initiation, especially for people with prolonged postural preparation or a high incidence of incomplete APAs.

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Abbreviations

PD	Parkinson's disease
FOG	Freezing of gait
APAs	Anticipatory postural adjustments
PD+FOG	Participants with FOG
PD-FOG	Participants without FOG
UPDRS	Unified Parkinson's disease rating scale
MoCA	Montreal cognitive assessment
CoP	Center of pressure
GRF	Ground reaction forces
CoPap1	Peak posterior excursion of the CoP during loading/unloading
CoPap2	Peak posterior excursion of the CoP near step leg toe-off
CoPml	Peak lateral excursion toward the step leg
BW	Body weight
ANOVA	Analysis of variance

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Highlights

- Cues markedly improved gait initiation in individuals with and without FOG.
- Temporally predictive cues improved APA timing more than random cues.
- Cueing improved APA timing most in individuals with prolonged self-initiated gait.
- Acoustic and visual cues were more effective than a vibrotactile cue.

Figure 1.

Figure 1. A: Paradigm for external cued and self-initiated protocols

Figure 1. B: Examples of anticipatory postural adjustments (APAs) during an acoustically cued and a self-initiated gait initiation trial in a participant with Parkinson's disease. The vertical arrows indicate the time points of the onset, peak and toe-off in the vertical ground reaction forces (GRF) on the step and stance legs and the onset and peak of the initial center of pressure excursions in the mediolateral (CoPml) and anteroposterior (CoPap) directions. Note the absence of an APA in the self-initiated example (no initial peak loading of the step leg, no peak unloading of the stance leg, no lateral or initial posterior excursions in the CoP).

Figure 2.

A: The average spatiotemporal characteristics of the initial peak posterior center of pressure excursions (CoPap1) during step initiation in self-initiated and visually cued conditions. The effect of cue timing only affected the duration, not the magnitude of peak CoPap1 in cued condition. Error bar indicates $\pm$ one SE. * indicates significant difference after Bonferroni adjustment. **B:** Correlation analyses between the change in performance induced by the cue (cued - self-initiated) and performance during the self-initiated condition in the time to step leg peak vertical GRF (top row) and peak amplitude of the step leg vertical GRF (bottom row) for acoustic (left column), visual (middle column) and vibrotactile (right column) cues. There were strong negative correlations between improvements in the timing of APAs evoked by cues (negative change values denoting decreased durations with a cue) and deficits in timing present during self-initiated stepping. In contrast, correlations between

cued-evoked changes in peak amplitude and self-initiated amplitude were mostly non-significant and weak. Line and marker color: blue, fixed delay; green, random delay; red, countdown. Abbreviation: NS, non-significant.

Table 1
Incidence of incomplete APAs (one or more components missing) during gait initiation

Cue modality	Self-initiated	Cue timing			Cued overall
		Fixed	Random	Countdown	
Acoustic (n = 25)					
Mean ± SD	17.1 ± 25.5 %	0 ± 0 %	0 ± 0 %	2.0 ± 7.3 %	0.7 ± 4.3 %
<i>P</i>		.006 *	.006 *	.023 *	<.001 *
Visual (n = 24)					
Mean ± SD	17.4 ± 26.0 %	0.7 ± 3.3 %	0 ± 0 %	2.0 ± 1.0 %	0.9 ± 6.2 %
<i>P</i>		.006 *	.007 *	.012 *	<.001 *
Vibrotactile (n = 20)					
Mean ± SD	17.2 ± 26.6 %	0.8 ± 3.6 %	1.6 ± 5.0 %	1.6 ± 5.0 %	1.4 ± 4.7 %
<i>P</i>		.097	.079	.133	<.001 *

Note: Bonferroni correction was applied to *P* values for pairwise comparison between each cue timing and self-initiated condition.

* Statistically significant.

Table 2

Characteristics of gait initiation in self-initiated and cued conditions

Dependent Variable	Mean $\pm$ SDD			
	Self-initiated	Fixed	Random	Countdown
Acoustic (n = 25)				
Reaction time (ms)	NA	133 $\pm$ 31	153 $\pm$ 45	96 $\pm$ 60
Time to peak step leg loading (ms)	340 $\pm$ 93	273 $\pm$ 69	290 $\pm$ 62	258 $\pm$ 59
Time to peak stance leg unloading (ms)	334 $\pm$ 90	265 $\pm$ 62	288 $\pm$ 66	260 $\pm$ 61
Time to step leg toe-off (ms)	740 $\pm$ 197	624 $\pm$ 123	644 $\pm$ 92	588 $\pm$ 102
Time to stance leg toe-off (ms)	1344 $\pm$ 245	1203 $\pm$ 169	1228 $\pm$ 120	1151 $\pm$ 147
Time to peak CoPap1 (ms)	375 $\pm$ 85	311 $\pm$ 78	343 $\pm$ 73	302 $\pm$ 78
Time to peak CoPap2 (ms)	732 $\pm$ 184	627 $\pm$ 108	653 $\pm$ 85	600 $\pm$ 94
Time to peak CoPml (ms)	343 $\pm$ 87	276 $\pm$ 64	300 $\pm$ 62	268 $\pm$ 59
Step leg peak loading (% BW)	1.1 $\pm$ 6.4	17.3 $\pm$ 6.9	16.4 $\pm$ 6.5	15.7 $\pm$ 7.2
Stance leg peak unloading (% BW)	1.4 $\pm$ 6.8	17.2 $\pm$ 6.6	16.4 $\pm$ 6.5	16.0 $\pm$ 7.0
Peak CoPap1 (cm)	2.4 $\pm$ 1.6	3.9 $\pm$ 1.6	3.7 $\pm$ 1.5	3.5 $\pm$ 1.7
Peak CoPap2 (cm)	2.9 $\pm$ 2.4	4.8 $\pm$ 2.1	4.5 $\pm$ 1.8	4.6 $\pm$ 2.0
Peak CoPml (cm)	2.5 $\pm$ 1.7	4.0 $\pm$ 1.7	3.8 $\pm$ 1.6	3.6 $\pm$ 1.6
Visual (n = 24)				
Reaction time (ms)	NA	181 $\pm$ 31	198 $\pm$ 44	157 $\pm$ 45
Time to peak step leg loading (ms)	339 $\pm$ 95	264 $\pm$ 51	283 $\pm$ 48	264 $\pm$ 41
Time to peak stance leg unloading (ms)	334 $\pm$ 92	262 $\pm$ 55	283 $\pm$ 50	262 $\pm$ 44
Time to step leg toe-off (ms)	738 $\pm$ 201	610 $\pm$ 98	642 $\pm$ 87	595 $\pm$ 78
Time to stance leg toe-off (ms)	1338 $\pm$ 249	1198 $\pm$ 150	1232 $\pm$ 119	1161 $\pm$ 134
Time to peak CoPap1 (ms)	376 $\pm$ 87	311 $\pm$ 72	330 $\pm$ 62	296 $\pm$ 53
Time to peak CoPap2 (ms)	731 $\pm$ 188	620 $\pm$ 75	646 $\pm$ 70	598 $\pm$ 69
Time to peak CoPml (ms)	343 $\pm$ 89	276 $\pm$ 53	292 $\pm$ 46	272 $\pm$ 43
Step leg peak loading (% BW)	1.2 $\pm$ 6.5	16.9 $\pm$ 6.8	16.7 $\pm$ 7.7	17.3 $\pm$ 7.3
Stance leg peak unloading (% BW)	1.5 $\pm$ 6.9	16.8 $\pm$ 6.8	16.7 $\pm$ 7.3	17.1 $\pm$ 6.9
Peak CoPap1 (cm)	2.5 $\pm$ 1.6	4.0 $\pm$ 1.7	3.9 $\pm$ 1.8	3.8 $\pm$ 1.9

Dependent Variable	Mean ± SDD			
	Self-initiated	Cue timing		
		Fixed	Random	Countdown
Peak CoPap2 (cm)	3.1 ± 2.3	5.0 ± 1.8	4.6 ± 1.9	4.6 ± 2.2
Peak CoPml (cm)	2.5 ± 1.7	4.0 ± 1.7	3.9 ± 1.7	3.9 ± 1.7
Vibrotactile (n = 20)				
Reaction time (ms)	NA	203 ± 26	243 ± 48	161 ± 77
Time to peak step leg loading (ms)	324 ± 70	302 ± 67	306 ± 82	287 ± 60
Time to peak stance leg unloading (ms)	321 ± 65	298 ± 67	306 ± 82	276 ± 61
Time to step leg toe-off (ms)	719 ± 127	678 ± 126	682 ± 121	649 ± 131
Time to stance leg toe-off (ms)	1293 ± 167	1233 ± 151	1252 ± 138	1189 ± 169
Time to peak CoPap1 (ms)	368 ± 62	352 ± 93	363 ± 86	325 ± 64
Time to peak CoPap2 (ms)	706 ± 106	677 ± 112	687 ± 110	646 ± 115
Time to peak CoPml (ms)	332 ± 65	311 ± 69	316 ± 83	286 ± 56
Step leg peak loading (% BW)	9.9 ± 6.8	14.7 ± 6.0	14.8 ± 6.5	13.5 ± 8.2
Stance leg peak unloading (% BW)	1.4 ± 7.4	15.0 ± 6.2	15.0 ± 6.6	13.8 ± 8.7
Peak CoPap1 (cm)	2.7 ± 1.6	3.8 ± 1.4	3.8 ± 1.5	3.1 ± 1.8
Peak CoPap2 (cm)	3.0 ± 2.4	4.5 ± 2.0	4.1 ± 2.3	3.9 ± 2.2
Peak CoPml (cm)	2.5 ± 1.8	3.5 ± 1.5	3.5 ± 1.7	3.2 ± 1.9

Abbreviations: NA, not applicable; BW, body weight; CoPap1, initial posterior excursion of center of pressure; CoPap2, secondary posterior excursion of center of pressure; CoPml, mediolateral excursion (toward stepping leg) of center of pressure.

Table 3

Summary of the statistical analysis of gait initiation in self-initiated and cued conditions

Dependent Variable	Condition		Interaction		Post hoc: condition		Post hoc: Interaction	
	df	F	P	P	Contrasts	Contrasts	Contrasts	Contrasts
Acoustic (n = 25)								
Reaction time (ms)	1.4	12.6	<.001	NS	R > C		NA	
Time to peak step leg loading (ms)	1.7	1.4	<.001	NS	S = R > F = C		NA	
Time to peak stance leg unloading (ms)	1.8	1.5	<.001	NS	S > F = C		NA	
Time to step leg toe-off (ms)	1.4	9.6	.001	NS	S = R > F = C		NA	
Time to stance leg toe-off (ms)	1.5	11.0	.001	NS	S = R > F = C		NA	
Time to peak CoPap1 (ms)	2.2	9.9	<.001	NS	S = R > F = C		NA	
Time to peak CoPap2 (ms)	1.5	8.4	.003	NS	S = R > C		NA	
Time to peak CoPml (ms)	1.8	1.8	<.001	NS	S = R > F = C		NA	
Step leg peak loading (% BW)	3	19.0	<.001	NS	F = R = C > S		NA	
Stance leg peak unloading (% BW)	2.3	17.0	<.001	NS	F = R = C > S		NA	
Peak CoPap1 (cm)	1.9	11.6	<.001	NS	F = R = C > S		NA	
Peak CoPap2 (cm)	3	16.0	<.001	.016	NA		PD-FOG: F = R = C > S; PD+FOG: F = R = C = S	
Peak CoPml (cm)	2.4	22.0	<.001	NS	F = R = C > S		NA	
Visual (n = 24)								
Reaction time (ms)	1.5	7.0	<.001	NS	R > F > C		NA	
Time to peak step leg loading (ms)	1.6	12.3	<.001	NS	S > R > F; S > C		NA	
Time to peak stance leg unloading (ms)	1.8	12.0	<.001	NS	S > R > F; S > C		NA	
Time to step leg toe-off (ms)	1.3	9.3	.003	NS	S > R > C; S > F		NA	
Time to stance leg toe-off (ms)	1.3	9.8	.002	NS	S > R > C; S > F		NA	
Time to peak CoPap1 (ms)	2.0	12.2	<.001	NS	S > R > F; S > C		NA	
Time to peak CoPap2 (ms)	1.2	9.1	.002	NS	S = R > F = C		NA	
Time to peak CoPml (ms)	1.7	11.7	<.001	NS	S > R > F; S > C		NA	
Step leg peak loading (% BW)	1.9	19.2	<.001	NS	F = R = C > S		NA	
Stance leg peak unloading (% BW)	1.8	17.2	<.001	NS	F = R = C > S		NA	
Peak CoPap1 (cm)	2.1	12.6	<.001	NS	F = R = C > S		NA	
Peak CoPap2 (cm)	3	15.9	<.001	.024	NA		PD-FOG: F = R = C > S; PD+FOG: F = R = C = S	

Dependent Variable	Condition		Interaction		Post hoc: condition		Post hoc: Interaction	
	df	F	P	P	Contrasts	Contrasts	Contrasts	Contrasts
Peak CoPml (cm)	1.9	21.9	<.001	NS	F = R = C > S	NA	NA	NA
Vibrotactile (n = 20)								
Reaction time (ms)	1.5	8.0	.003	NS	R > C	NA	NA	NA
Time to peak step leg loading (ms)			NS	NS	NA	NA	NA	NA
Time to peak stance leg unloading (ms)			NS	NS	NA	NA	NA	NA
Time to step leg toe-off (ms)			NS	NS	NA	NA	NA	NA
Time to stance leg toe-off (ms)	3	6.3	.001	NS	S = R > C	NA	NA	NA
Time to peak CoPap1 (ms)			NS	NS	NA	NA	NA	NA
Time to peak CoPap2 (ms)			NS	NS	NA	NA	NA	NA
Time to peak CoPml (ms)			NS	NS	NA	NA	NA	NA
Step leg peak loading (% BW)	1.9	8.6	.001	NS	F = R = C > S	NA	NA	NA
Stance leg peak unloading (% BW)	1.8	7.2	.003	NS	F = R = C > S	NA	NA	NA
Peak CoPap1 (cm)	2.1	8.7	.001	NS	F = R > S = C	NA	NA	NA
Peak CoPap2 (cm)	3	6.0	.001	.042	NA	PD-FOG: F = R = C > S; PD+FOG: F = R = C = S S: PD+FOG > PD-FOG	NA	NA
Peak CoPml (cm)	2.1	9.0	.001	NS	F = R = C > S	NA	NA	NA

Abbreviations: BW, body weight; CoPap1, initial posterior excursion of center of pressure; CoPap2, secondary posterior excursion of center of pressure; CoPml, mediolateral excursion (toward stepping leg) of center of pressure; S, self-initiated; F, fixed delay; R, random delay; C, countdown; NS, non-significant; NA, not applicable; PD-FOG, non-freezer group; PD+FOG, freezer group. Note: The column Post hoc: condition shows the contrast summary using Bonferroni adjustment. For example, the significant contrasts in the Time to peak step leg loading in the acoustic condition are: S > F, S > C, R > F and R > C. This is summarized into S = R > F = C.