Modulation of Anticipatory Postural Adjustments of Gait Using a Portable Powered Ankle-Foot Orthosis

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***Abstract*— Prior to taking a step, properly coordinated anticipatory postural adjustments (APAs) are generated to control posture and balance as the body is propelled forward. External cues (audio, visual, somatosensory) have been shown to facilitate gait initiation by improving the magnitude and timing of APAs in Parkinson's disease (PD), but the efficacy of these cueing strategies has been limited by their inability to produce the forces required to generate an appropriate APA. To date, mechanical cueing paradigms have been relatively underexplored. Using healthy young adults, we investigated the use of a portable powered ankle-foot orthosis (PPAFO) to provide a modest torque at the ankle as a mechanical cue to initiate gait. Subjects were instructed to initiate gait in five test conditions: (1) self-initiated in running shoes [baseline-shoe], (2) self-initiated trial in unpowered passive PPAFO [baseline-passive], (3) with acoustic go-cue in passive PPAFO [acoustic-passive], (4) acoustic go-cue and simultaneous mechanical assist from powered PPAFO [acoustic-assist], and (5) mechanical assist cue only [assist]. APA characteristics were quantified using ground reaction force (GRF), center of pressure (COP), and electromyography (EMG) data. Mechanical cueing significantly increased medial-lateral COP and GRF peak amplitude, and decreased GRF time to peak amplitude, COP and GRF onset times, and time to toe off. Mechanical cueing conditions also demonstrated consistent bimodal EMG behaviors across all subjects. Overall, these data suggest that the mechanical assist from the PPAFO can significantly improve APA timing parameters and increase APA force production in healthy young adults.**

Keywords—powered orthosis, exoskeleton, cueing, anticipatory postural adjustments, gait initiation)

I. INTRODUCTION

During the transition from standing to stepping forward, anticipatory postural adjustments (APAs) are generated prior to the step [1]. The typical sequence of APAs observed during gait initiation include simultaneous loading of the stepping leg, unloading of the stance leg, movement of the center of pressure (COP) posterior and toward the stepping leg, an initial burst of activity in the tibialis anterior muscle of the stepping leg, and flexion of the stepping limb hip and knee (**Figure 1**). This motor sequence generates the forces required to accelerate the center of mass forward and laterally toward the stance limb at the start of the step, thus providing both posture and balance control, as well as forward propulsion.

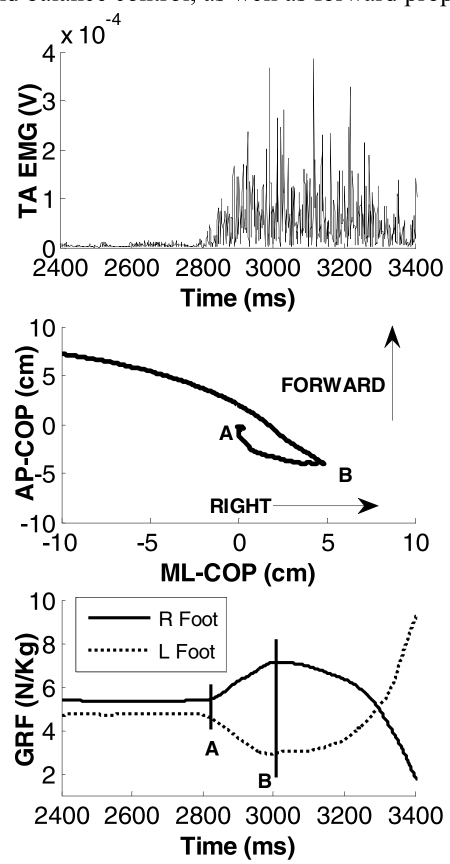

Fig. 1. Characteristics of APAs for gait initiation starting with the right leg in a healthy adult that begins at point A. The plots show right tibialis anterior (TA) EMG, center of pressure (COP), and vertical ground reaction forces (GRF) for the right (stepping) and left (stance) limbs.

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In Parkinson's disease (PD), APAs for gait initiation are reduced in amplitude, prolonged in duration and often inappropriately timed with the forward step, resulting in the termination or shortening of the initial step. Clinicians have long recognized that one of the best methods to facilitate movement initiation in patients with PD is to provide them with a visual, acoustic or somatosensory cue. Laboratory studies have provided quantitative evidence to support this observation by showing that cues can significantly improve the initiation of gait [2]. Despite evidence that cues can facilitate movement initiation in people with PD, the results of studies examining the effectiveness of cues in the home environment have yielded disappointing results [3-6]. This lack of effectiveness could be due in large part that current cueing paradigms do not compensate for reduced capacities to generate the forces necessary to successfully transfer the center of mass laterally during gait initiation. Therefore, there is a need for more reliable cueing interventions that are also able to facilitate force production.

Providing mechanical assistance as a cue has been relatively underexplored. Two recent studies have examined the effects of using an externally applied perturbation. One involved a lateral pull at the waist [7] and the other utilized raising/dropping the floor underneath the initial stance foot [8] to facilitate medial-lateral adjustments in posture and balance prior to step initiation in PD patients with FOG. Both interventions were associated with significant shortening of APA duration and earlier step onset. The dropping floor protocol was also able to significantly improve vertical loading/unloading force magnitude of the stepping/stance legs, respectively. These results suggest that a mechanical perturbation which augments loading behaviors during an APA can improve gait initiation in individuals with FOG.

We have recently developed a portable powered ankle-foot orthosis (PPAFO) to provide untethered assistance during gait (**Figure 2)** [9, 10]. It has been demonstrated to restore normative gait function in neurological disorders such as cauda equina syndrome and muscular dystrophy. The PPAFO utilizes a bi-directional pneumatic rotary actuator (CRB2BW40-90D-DIM0065, SMC Corp of America; Noblesville, Indiana) powered by a compressed CO_2 gas tank that can be worn at the belt (JacPac J-6901-91, 20 oz capacity; Pipeline Inc., Waterloo, ON, Canada) to provide dorsi and plantarflexor torque at the ankle. It is capable of producing up to 12 Nm of torque at 0.69 MPa (100 psi). Using on-board electronics, control strategies have been developed to provide assistance at specific times in the gait cycle [11] and to adapt to different walking environments (stairs, ramps) [12]. The purpose of the current study was to investigate how modest torques at the ankle delivered by the PPAFO can modulate APA behaviors during gait initiation. We hypothesize that by driving the ankle through typical APA movements for gait initiation with the PPAFO, participants will generate more force than that seen in self-initiated conditions.

II. Methods

A. Subjects

Five healthy young adults (4 male, 1 female, age 21±2 yrs, height 183.6±6.1 cm, weight 78.8±11.5 kg) were tested in this study.

B. Gait Initiation Task

In order to test its efficacy, mechanical cueing from the PPAFO was compared with an acoustic cue in the form of an auditory beep and providing mechanical assistance along with the acoustic cue. Test subjects were asked to initiate gait from a standing position by first stepping with the right leg. Five gait-initiation test conditions were evaluated: (1) self-initiated in personal walking shoes to provide normal baseline [baseline-shoe], (2) self-initiated trial in unpowered passive PPAFO to provide baseline while wearing PPAFO [baseline-passive], (3) acoustic go-cue with passive PPAFO to assess effect of acoustic cue [acoustic-passive], (4) acoustic go-cue with simultaneous mechanical assist from powered PPAFO to assess effect of acoustic and mechanical assist cue [acoustic-assist], and (5) only mechanical assist cue from powered PPAFO [assist]. The PPAFO was fit to the test participant and worn on the right limb. The participant's personal walking shoe was worn on the left limb **(Figure 2)**.

Blocks of 5 trials were performed for each test condition (total of 25 trials per participant). Trials for test condition (1) were run consecutively before the remaining four conditions. Trial order was randomized for conditions (2-5). Before each trial, subjects were told whether it was a cued or self-initiated trial. For conditions 1 and 2, subjects were instructed to initiate gait with their right foot on their own within 5-10 seconds after hearing the warning signal (**Figure 3)**. For conditions 3-5, they were instructed to initiate gait with their right foot "as quickly as possible" taking a minimum of two steps forward in response to the go-cue. No practice trials were given before the test started.

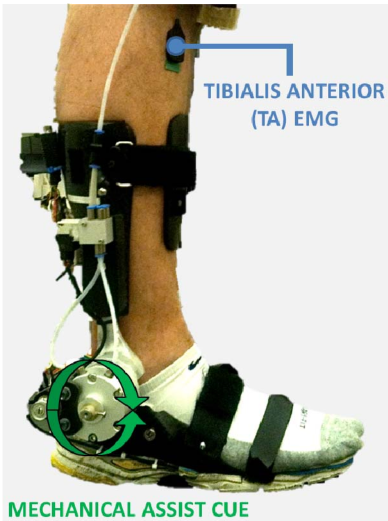

Fig.2. Experimental set up with the PPAFO attached to the right leg. Ground reaction force (GRF) data were recorded from two force plates under each foot. Bipolar surface EMG signals were recorded from an electrode placed over the right tibialis anterior (TA).

C. Cue Presentation

It has been recently shown that gait initiation can be significantly improved in people with PD when the imperative cue to initiate stepping is preceded 2.5 s earlier by a warning cue (an instructed-delay paradigm) [13]. For conditions 3-5 we used a similar instructed-delay paradigm consisting of an acoustic warning cue presented 2.5 s before the imperative go-cue (acoustic and/or mechanical) to initiate a forward step with the right foot **(Figure 3)** [14].

The instructed-delay warning, acoustic go-cue, and actuation of the PPAFO for the mechanical assist cue were all controlled with custom software (QUARC, Quanser Consulting Inc, Markham, ON, Canada). Both the acoustic warning and go-cue were clearly audible tones for 500 ms at 80 dB from a speaker. The mechanical assist cue began with a dorsiflexor torque (heuristically tuned to hold the subjects toes at neutral, approximately 3-5 N-m) delivered for 330 ms and followed with a subsequent plantarflexor torque of 9 Nm (based on 90 psig actuated pressure) for 83 ms which terminates at toe-off (timings based on average time to peak from APA onset and toe-off time in healthy control subjects [13]). This pattern of torques matches activities normally seen in gait initiation.

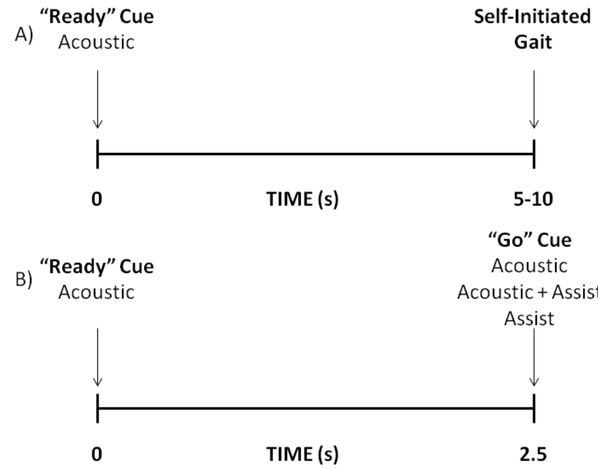

Fig. 3. A) Timeline for self-initiated trials. Subject initiates gait within 5-10 seconds of the "ready" warning cue. B) Instructed-delay timeline for the cued trials. The imperative "go" is given 2.5 s after the "ready" warning cue.

D. Data Collection

Ground reaction force (GRF), center of pressure (COP), and electromyographic (EMG) data were recorded and sampled at 1000 Hz. The subject stood with each foot on separate force plates. The force plates were embedded in an instrumented treadmill (Bertec Corporation, Columbus, OH). Force data were filtered using a low-pass Butterworth filter with a cut-off frequency of 15 Hz. Net center of pressure under both feet (COP) for the medial-lateral (ML) and anterior-posterior (AP) directions were calculated using filtered GRF data. Bipolar surface EMG signals (Bagnoli 16, Delsys Corp., Boston, MA) were recorded from only the right tibialis anterior (TA).

E. Data Analysis

To quantify the APA response to the different test conditions, 11 parameters were computed from the vertical GRF and TA EMG of the right leg, and total body AP and ML COP (**Figure 4**). For the test conditions with acoustic and/or mechanical assistance, the times from the imperative go-cue to the onset of each parameter were determined for vertical reaction force (GRF_t_{onset}), AP center of pressure (AP-COP_t_{onset}), ML center of pressure (ML-COP_t_{onset}), and TA EMG signal (EMG_t_{onset}). For all test conditions, the magnitudes of the peak amplitude and the times from onset to the peak amplitude were recorded for vertical GRF (GRF_{pk}, GRF_t_{pk}), AP center of pressure (AP-COP_{pk}, AP-COP_t_{pk}), and ML center of pressure (ML-COP_{pk}, ML-COP_t_{pk}). Additionally, the time from onset to the start of toe off was recorded based on the time when the right vertical GRF went below 30 Nm ($t_{toe\text{-}off}$). GRFs were normalized as a percentage of a subject's body weight. Onset times were calculated based on a monotonic change of greater than three standard deviations from the mean signal that was recorded prior to the go-cue. For the baseline conditions that did not contain a go-cue, the mean signal was calculated prior to a point manually picked approximately 300-500 ms before GRF_t_{onset}. These times were further verified by visual inspection.

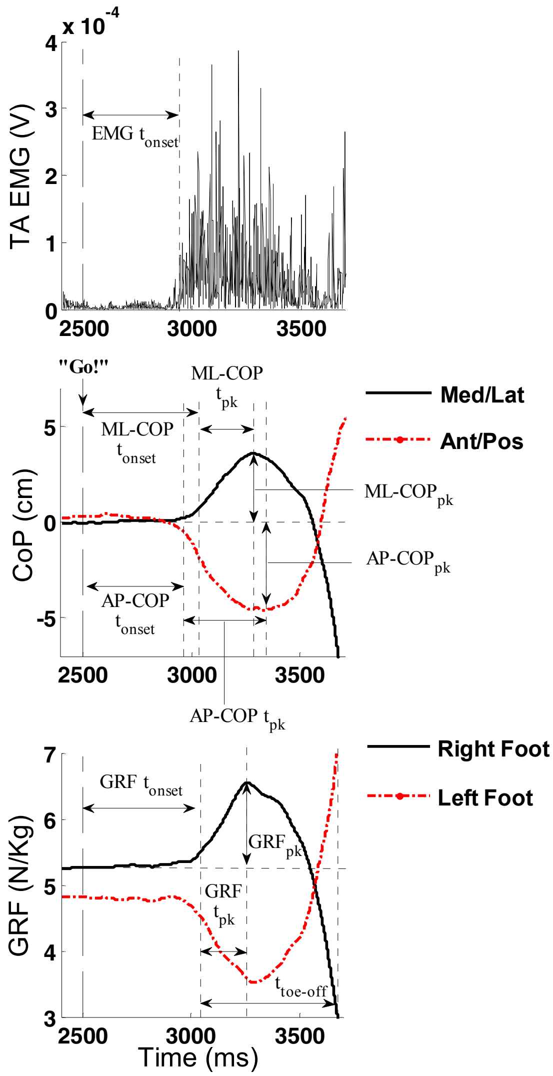

Fig 4. Illustration of the 11 GRF, COP and EMG APA parameters. Go-cue is represented as the thicker dashed line at 2500 ms.

F. Statistical Analysis

Repeated-measures analysis of variance (ANOVA) tests were conducted to assess the effect of testing condition on the 11 APA parameters. Based on a Bonferroni adjustment for multiple statistical comparisons, we regarded p values less than 0.005 to indicate a significant association, and p values between 0.05 and 0.005 to reflect a "borderline" association. Post hoc effects were examined using Fisher LSD (Least Significant Difference) test. All data were processed using SPSS statistical software (Version 20, IBM Corp, Armonk, NY).

III. RESULTS

Repeated-measures ANOVAs indicated statistically significant ($p < 0.005$) or borderline significant ($0.005 < p < 0.05$) differences due to testing condition in seven of the eleven APA parameters (**Table I**).

A. Ground Reaction Forces

All APA parameters associated with the vertical GRF for the stepping (right) leg were affected due to the use of the mechanical cueing from the PPAFO (**Table I**). Onset time (from go-cue to rise of GRF, GRF_t_{onset}) was significantly faster when the mechanical assist from the PPAFO was used compared to only acoustic cueing ($p = 0.004$). When the mechanical assist was used alone, the peak amplitude of the GRF (GRF_{pk}) was significantly larger than any condition without the mechanical cueing assistance ($p = 0.001$). The times to the peak GRF value (GRF_t_{pk}) tended to be faster for conditions with mechanical assist ($p = 0.006$). Similarly, the times to the start of toe-off ($t_{toe\text{-}off}$) tended to be faster in mechanical assist trials ($p = 0.037$).

B. Center of Pressure

Analogous to GRF parameters, mechanical cueing assistance affected both timing and peak displacement of center of pressure parameters. Medial-lateral onset time (ML-COP_t_{onset}) was significantly shortened by mechanical cueing compared to acoustic cueing ($p = 0.003$). Medial-laterial peak displacement ($ML\text{-}COP_{pk}$) was signficantly increased by cueing compared to baseline conditions, and mechanical assistance resulted in the largest movement of the COP ($p < 0.001$). Likewise, mechanical assitance accompanied by an acoustic cue tended to shorten anterior-poserior onset time (AP-COP_t_{onset}) when compared to acoustic cueing alone ($p = 0.027$).

C. Electromyography (EMG)

Although not significantly different, EMG onset time (EMG_t_{onset}) tended to be consistently shorter with mechanical cueing compared to the other conditions. A bimodal pattern in the TA muscle activity was consistently observed, supporting activation during APA onset, suppression during plantarflexion, and activation during late toe-off (**Figure 5**).

TABLE I. AVERAGE VALUES ± STANDARD DEVIATION FOR ALL PARAMETERS BY CONDITION. SUPERSCRIPTS INDICATE SIGNIFICANT DIFFERENCE FROM INDICATED CONDITION (P < 0.005, UPPERCASE) OR BORDERLINE SIGNFICANT (0.005 < P < 0.05, LOWERCASE).

Conditions (A-E)	**(A) Baseline Shoe**	**(B) Baseline Passive**	**(C) Acoustic**	**(D) Acoustic + Assist**	**(E) Mechanical Assist**	**p-value**
GRF_t_{onset} (ms)	-	-	$391 \pm 194^{D,E}$	215 ± 59^{C}	239 ± 83^{C}	**0.004**
GRF_{pk} (N)	1.3 ± 0.6^{E}	1.4 ± 0.5^{E}	1.9 ± 0.6^{E}	2.5 ± 0.9	$2.7 \pm 0.7^{A,B,C}$	**0.001**
GRF_t_{pk} (ms)	318 ± 125^{d}	356 ± 144^{d}	$317 \pm 120^{d,e}$	$263 \pm 73^{a,b,c}$	284 ± 97^{c}	*0.006*
$t_{toe\text{-}off}$ (ms)	606 ± 152	$584 \pm 195^{d,e}$	582 ± 139^{e}	503 ± 134^{b}	$530 \pm 135^{b,c}$	*0.037*
AP-COP_t_{onset} (ms)	-	-	415 ± 167^{d}	244 ± 80^{c}	279 ± 137	*0.027*
$AP\text{-}COP_{pk}$ (mm)	59 ± 16	53 ± 13	61 ± 14	66 ± 12	64 ± 14	0.125
AP-COP_t_{pk} (ms)	405 ± 108	462 ± 123	392 ± 131	347 ± 120	330 ± 110	0.054
ML-COP_t_{onset} (ms)	-	-	$405 \pm 187^{D,E}$	232 ± 40^{C}	267 ± 72^{C}	**0.003**
$ML\text{-}COP_{pk}$ (mm)	$45 \pm 23^{C,E}$	$47 \pm 18^{C,D,E}$	$57 \pm 25^{A,B,E}$	74 ± 22^{B}	$84 \pm 25^{A,B,C}$	**< 0.001**
ML-COP_t_{pk} (ms)	350 ± 142	362 ± 142	298 ± 128	241 ± 82	253 ± 83	0.060
EMG_t_{onset} (ms)	-	-	273 ± 128	182 ± 68	164 ± 68	0.115

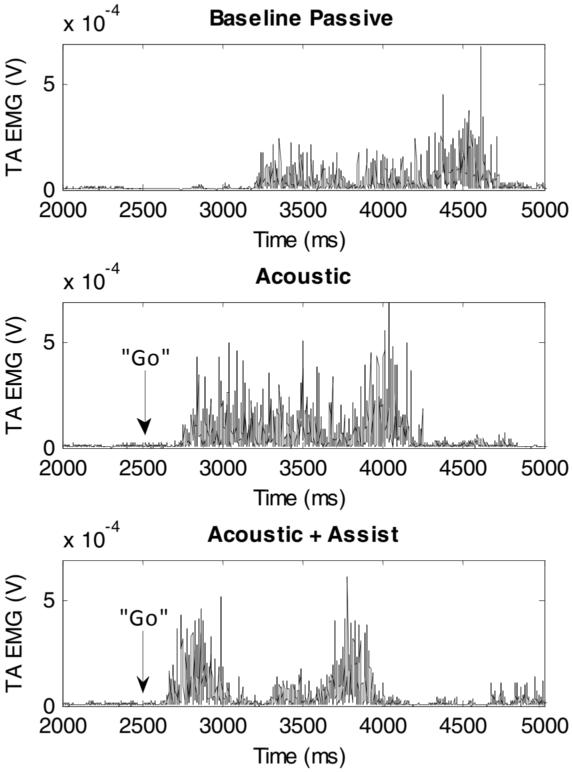

Fig. 5. EMG recording from the right TA, during each of the gait initiation conditions.

IV. Discussion

The main finding of this study was that mechanical assistance provided from a PPAFO can be used as a somatosensory cue to induce consistent normal APA behaviors (**Table I**). The increased force production due to the ankle torque assistance from the PPAFO resulted in a larger displacement of the center of pressure in the medial-lateral direction, which reflects the desired lateral weight transfer. Temporal characteristics were also shortened suggesting faster step initiation. EMG activity of the TA muscle also had a consistent bimodal behavior showing distinct activation, as expected during an APA. Overall, the data suggest that a mechanical assist (with or without acoustic cue) may be used as a potential cueing paradigm for gait initiation.

The underlying neural mechanisms that enable cues to work in people with PD are poorly understood. Cues have been demonstrated to elicit improved APAs in PD, i.e., similar or greater performance as compared to when a person is on levodopa medication [2, 15]. This result suggests that the neural pathways used to generate motor commands for postural and locomotion are able to function independent of dopaminergic pathways. As proposed by Rogers et al [13], cues may act as a way of increasing preparation for movement and are processed in non-dopaminergic pathways in areas within the corticospinal tract. Studies in people with PD show an increase of activity in the lateral premotor and parietal cortices during movement [16-19]. This neural activity in the premotor cortex is amplified at the beginning of the intended movement when a cue is given in an instructed-delay paradigm compared to in self-paced trials [20]. At the same time, this neural activity is diminished when the cue is given at a random time interval when compared to self-paced trials. Given the instructed-delay paradigm has been shown to elicit APAs in people with PD consistently, using a fixed warning time interval may be a reliable paradigm for inducing gait APAs independent of dopaminergic pathways.

Although these data were recorded on healthy normal young adults, the results of this study may have potential implications for gait initiation in PD. Both healthy and PD subjects have been shown to elicit APA behavior in an instructed delay paradigm in up to 80% of trials [13, 14]. There is little insight into whether the duration of the mechanical assistance would impede or exacerbate APAs due to how little mechanical perturbations have been investigated as a cue. Previous studies used time durations as low as 100 ms to elicit an APA in people with PD [8], which is shorter than what was used in the current protocol for the dorsiflexion torque. Future studies would have to be done to optimize the timing of the PPAFO actuations such that it will only provide assistance and not impede APAs. Most importantly, the amplified and shortened APAs observed using mechanical assistance from the PPAFO may be able to counteract the slower and under-scaled APAs that have been observed in people with PD [13]. Thus, a mechanical assist from the PPAFO may be able to induce the necessary loading/unloading behaviors that are absent in people with severe PD.

V. Conclusions

These data suggest that the mechanical assist from the PPAFO can signifcantly improve APA parameters and increase APA force production for healthy normal young adults. Further studies should include people with PD to test the feasibility of using the PPAFO for cueing of Parkinsonian gait.

VI. Acknowledgments

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