THE POSTERIOR SHIFT ANTICIPATORY POSTURAL ADJUSTMENT IN CHOICE REACTION STEP INITIATION

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1. Introduction

Falls are a major source of injury and death among the elderly population (Melzer, 2014, St George, 2007, Cohen, 2011, Sparto, 2013, Sparto, 2014). Rapid postural adjustment to restore center of mass (COM) equilibrium after loss of balance (slip, trips, etc) is critical for the prevention of falls (St George, 2007, Cohen, 2011, Melzer, 2007, Melzer, 2007). The most common approach for compensation of a postural perturbation is to initiate a step to increase the base of support as well as decelerate the speed of COM movement (Mickelborough, van der Linden, Tallis, & Ennos, 2004). The speed of voluntary step initiation has been shown as an important predictor for fall detection among the elderly population (Lord & Fitzpatrick, 2001; Itshak Melzer, Shtilman, Rosenblatt, & Oddsson, 2007; Itshak Melzer et al., 2007; St George, Ritzpatrick, Rogers, & Lord, 2007). To minimize the risk of falling, the cognitive processing, weight transfer, and locomotion components of a step must be timed and executed appropriately (Rogers, Kukulka, Brunt, Cain, & Hanke, 2001; St George et al., 2007; Uemura, Oya, & Uchiyama, 2013). Thus, the aforementioned components during step initiation were studied to investigate the cognitive processing to prepare and execute a step.

Step initiation can be divided into 5 stages (see Fig. 1): 1) the RT lasts from the stimulus delivery to the onset of center of pressure (COP) deviation; 2) the release phase lasts from the COP onset until the furthest point of postero-lateral COP (MaxCOP); 3) the unloading phase lasts from the MaxCOP to the swing foot toe off the ground (SWTO); 4) the single support phase (SSP) or swing phase lasts from the SWTO to the swing foot initial contact (SWIC); 5) the double support phase (DSP) lasts from the SWIC to the stance foot toe off ground (STTO). Stages 2 and 3 combined are defined as the APA phase, while stages 4 and 5 combined are defined as the stepping phase (Cohen, Nutt, & Horak, 2011; Dalton, Bishop, Tillman, & Hass, 2011; MacKinnon et al., 2007; I Melzer, Kurz, Shahar, Levi, & Oddsson, 2007; Itshak Melzer & Oddsson, 2004; Itshak Melzer et al., 2007; Mickelborough et al., 2004; Sparto et al., 2013; Uemura et al., 2013).

Previous studies have identified Anticipatory Postural Adjustment (APA) as a marker of preparatory movement during step initiation (Cohen et al., 2011; Uemura et al., 2013). The APA is defined as lateral weight transfer towards the swing foot preceding a step. It is believed to stabilize posture and generate the initial momentum needed to begin walking (Dalton et al., 2011). Multiple studies report that errors (Cohen et al., 2011; Sparto et al., 2013; Uemura et al., 2013) in the initial weight transfer, which is defined as APA error, lead to slow choice step execution due to additional time for error correction before a step can safely take place.

The present study examined the effects of choice on the temporal characteristic of step initiation. The study also aimed to investigate the impact of APA on step characteristics. Previous studies on APA error were limited to a binary choice situation in which APAs were either correct or incorrect based on the shift direction in weight transfer (Cohen et al., 2011; Sparto et al., 2013; Sparto, Jennings, Furman, & Redfern, 2014; Uemura et al., 2013). According to decision theory (Busemeyer & Townsend, 1993; Roe, Busemeyer, & Townsend, 2001; Simonson, 1989), human behavior tends to reflect a compromise effect in which subjects add an intermediate alternative that lies between the two competing extreme options in the original choice set. Therefore, we hypothesized that by analyzing the COP trajectory, we could identify the compromise effect during the reaction and APA phase of step initiation.

2. Method

2.1 Participants

Nine healthy young subjects (six female, three male, $M = 21.9 \pm 1.3$ years old, right leg dominant according to self-report) participated in this study. None of the participants had a history of orthopedic injury, musculoskeletal, vestibular, neurological disorders or stroke according to self-report. All participants gave informed consent prior to participation in the study. The study was approved by the Institutional Review Board of Indiana University.

2.2 Task and Design

Subjects were instructed to stand upright and barefoot on a force platform, with their feet 20 cm apart. The perimeter of participants' feet was marked with tape to ensure consistent stance throughout the experiment. Subjects looked straight ahead during the entire trial, with eyes open, fixating on a target placed 3 m ahead at eye level. After a warning signal and a random foreperiod between 2-5 s, subjects received an auditory cue and initiated a forward step onto a second force platform as quickly as possible. Subjects stepped forward with the foot corresponding to the pitch of the auditory cue, and then brought the stance foot next to the stepping foot. The two sound pitches were 250 Hz (**low pitch**) for left leg stepping, and 500 Hz (**high pitch**) for right leg stepping. In the SRST condition, participants were informed that the auditory cue would signal either the left (SRST-L) or right (SRST-R) leg stepping for the entire block of trails. In the CRST condition, participants were informed that the auditory cue was equally likely to signal left (CRST-L) or right (CRST-R) leg stepping. The SRST condition was blocked and counterbalanced with every participant completing 10 trials in the SRST-L and SRST-R conditions. To prevent subject anticipation and movement preprogramming, the CRST consisted of 25 trials with at least 10 trials stepping with left or right leg. Catch trials (1000 Hz sound buzzer) in which subjects were required to abort stepping were included in all testing blocks at a rate of 20% of total number of trials. Subjects sat and rested for 5 min between trial blocks.

2.3 Data Recording and Analysis

A Tekscan HR MAT Pressure Mat (Tekscan Inc.) was mounted on top of a forceplate (AMTI). The HR MAT allowed the experimenter to monitor and maintain the participant's weight distribution under both feet evenly (with no more than 51% of weight on either foot) before starting the trial (Cohen et al., 2011). Ground reaction forces (GRFs) and moments were collected from the forceplate at 1000 Hz. The COP was derived from the forces and moments.

The auditory stimuli (250 Hz / 500 Hz / 1000 Hz, 85 dB, 100 ms) were generated from a customized LABVIEW program (National Instruments). Tones were presented via 2 loudspeakers (< 1 ms rise time) located at 2 m height and 2 m away bilaterally from the participant. The stimulus intensities were measured using a sound level meter. All analog signals were synced and recorded with the motion analysis system (Qualisys AB, Sweden) through a 64 channel A/D board, and sampled at 1000 Hz.

Step initiation event timings were calculated for each trial from the COP data, as well as vertical velocity of toe and heel markers (Mickelborough et al., 2004) (sampled at 100 Hz) recorded by the Qualisys system. Specific temporal events were extracted from the step initiation data using a customized program written in MATLAB (MathWorks.Inc.). The movement onset was identified as when COP velocity was greater than 3 standard deviations from the baseline value calculated from a 0.5 s window before stimulus onset (MacKinnon et al., 2007). The point of maximum postural lateral COP displacement (MaxCOP) was identified as the end of COP mediolateral shift toward the swing leg (absolute COP velocity < 100 mm/s). Swing Toe Off (SWTO) was defined as the end of the COP mediolateral shift toward the stance leg (Itshak Melzer

& Oddsson, 2004). Swing Leg Initial Contact (SWIC) was determined using the sudden increase of GRF on the second force platform. Stance Leg Toe Off (STTO) was determined as the point when GRF under the 1st forceplate dropped to below 10 N level.

2.4 Statistical Analysis

Before analyzing data, we excluded trials on which participants 1) initiated an APA sooner than 80 ms after the audio cue (Cohen et al., 2011; Shelton & Kumar, 2010), 2) failed to step within 2 s after the audio cue, and 3) stepped with the wrong foot. This left 347 trials (171 SRST, 176 CRST), on average 39 trials per subject. For analysis, a two-way repeated measures analysis of variance (ANOVA) was first performed, in which stepping task (SRST vs CRST) and stepping leg (left vs right) were used as the fixed factors and subjects as the random factor. To determine how APA responses affected the timing of each step initiation phase (RT, Release, Unloading, SSP, DSP), a secondary analysis was performed on CRST data using a linear mixed model with APA types (Correct, Error and Posterior Shift) and stepping leg as fixed factors and participant as a random factor. We used post hoc testing (Tukey HSD) to further investigate the role of APA response type. Alpha was set at .05 for all tests. COP sway path length, and its correlation with the duration in each step initiation stage was calculated.

3. Results

Examples of one subject's COP spatial evolution during choice reaction stepping trials are shown in Fig. 2. Three types of APA response were classified based on the COP velocity profile in the M/L and A/P direction during release phase: 1) Correct APA (COP shifts postero-laterally toward the swing leg); 2) Error APA (COP shifts postero-laterally toward the stance leg, and then turning back to the swing leg); 3) Posterior Shift (PS) APA (COP shifts in the posterior direction before turning toward the swing leg). In the PS APA trials, the posterior COP velocity increased above 3 SD from its static baseline value at least 50 ms prior to lateral COP velocity onset. In the correct and error APA trials, the lateral and posterior COP velocity onset latency was within 50ms. All SRST trials were determined as Correct APA trials. In the CRST condition, there were 51 Correct APA trials, 65 Error APA trials, and 60 PS APA trials. Mean and SD of the duration in each stepping stage are summarized in Table.1.

3.1 Influence of stepping task (SRST vs CRST) on response times during step initiation

Significant main effects of stepping task were observed (Fig. 3-A) on RT, $F(1,335) = 151.9$, $p < .001$; Release phase, $F(1,335) = 112.9$, $p < .001$; Unloading phase, $F(1,335) = 27.8$, $p < .001$; and DSP, $F(1,335) = 39.0$, $p < .001$. All aforementioned durations in CRST were longer than in SRST. The difference for SSP duration between SRST and CRST was not significant ($p > .05$). The total step execution time, which was the summation of the five stages, in SRST was 250 ms shorter than in CRST, $F(1,335) = 420.3$, $p < .001$.

The effect of stepping leg was only significant in the DSP, $F(1,335) = 23.4$, $p < .001$. The duration of DSP was longer for the right stepping leg than for the left stepping leg (Left, 256 ms; Right, 274 ms).

3.1.1 **Influence of stepping task (SRST vs CRST) on response times among APA correct trials**

SRST and Correct APA CRST trials were analyzed to further determine the impact of stepping task on the timing of step initiation. Fig. 3-B shows significant main effects of stepping task on RT, $F(1,220) = 219.3$, $p < .001$; Unloading phase, $F(1,220) = 22.4$, $p < .001$; SSP, $F(1,220) = 4.3$, $p = .039$; and DSP, $F(1,220) = 17.1$, $p < .001$. All temporal characteristic results except the duration of the release phase were significantly shorter in the SRST than in the CRST condition. The difference between SRST and CRST for the release phase duration was not significant.

The effect of stepping leg was only significant in the DSP, $F(1,335) = 15.3$, $p < .001$, in which its duration was longer with the right stepping leg than the left stepping leg (Left, 256 ms; Right, 273 ms).

3.2 Influence of APA types on CRST response time

The effect of APA types was significant (see Fig. 4) for RT, $F(2,164) = 12.5$, $p < .001$; release phase, $F(2,164) = 69.1$, $p < .001$; unloading phase, $F(2,164) = 6.1$, $p = .003$; SSP, $F(2,164) = 12.2$, $p < .001$; and the total step execution time, $F(2,164) = 16.5$, $p < .001$. The post hoc test showed that the APA Correct response trials had 100 ms longer RT than the Error and PS trials. For release phase duration, the Error APAs were 200 ms longer than the Correct APAs, the PS APAs were 100 ms longer than the Correct APAs. The unloading phase duration for the PS APA was 25 ms shorter than the other two response types. For the SSP duration, the Error APAs were 70 ms shorter than the Correct APAs, while the PS APAs were 30 ms shorter than the Correct APAs. No difference was observed for the DSP duration among the 3 APA response types. For total step execution time, the PS APAs were 100 ms shorter than the other 2 APA types. Significant positive correlations between COP sway length and timing of phases were noted for the Release ($\rho = .27$, $p < .001$), Unloading ($\rho = .31$, $p < .001$) and DSP phases ($\rho = .57$, $p < .001$).

The effect of stepping leg was only significant in the DSP, $F(1,164) = 23.4$, $p < .001$, in which its duration was longer with the right stepping leg than the left stepping leg (Left,260 ms; Right, 293 ms).

4. Discussion

This study tested the hypothesis that RT would be longer for the CRST than for the SRST. Findings showed that not only RT was sensitive to the additional processing in stimulus evaluation and response selection, but the release, unloading, and double support phases were also sensitive to the addition of choice. This indicates that stimulus evaluation was not completed before movement execution. As the stimulus was evaluated during the APA phase, the delay latency caused by the CRST in later stages (Unloading, DSP) of step initiation was not slowed as much as in the early stages (RT, Release).

We found that RT was lengthened in trials with correct APAs, while the APA release phase in the APA error trials was significantly prolonged compared to the APA correct trials. This was mainly derived from initial motor program error and its correction, as described by Uemura *et al* (Uemura et al., 2013). In trials with correct APAs, the longer RT can be attributed to a cautious response, as the subject focused on accuracy at the expense of speed in performance (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Dutilh, Wagenmakers, Visser, & van der Maas, 2011). Despite the longer RT in correct APAs, the overall stepping time was not prolonged compared to APA error trials. This is because the time to correct the initial motor program error during the release phase outweighs the fast latency of RT. A similar finding was reported in a study by Cohen *et al* (Cohen et al., 2011) in which step latency (defined as the summation of RT, release, and unloading phase) was compared between trials with and without APA error. It was found that a wrong initial motor program delayed the step latency. Our data regarding the step latency confirmed their findings. However, by taking into account the stepping phase (SSP and DSP), we found that subjects make up for their errors by speeding up the single support phase. Therefore, the overall time for completing a step was no different from the trials with correct APAs.

The posterior shift (PS) APA had a fast RT similar to the Error APA trials, while the release phase duration was intermediate between Correct and Error APA trials. The fast RT indicates that motor preparation was pre-programmed ahead of stimulus delivery among the APA error and PS trials. Subjects in PS trials, however, did not program the response towards either leg with 100 percent certainty. Thus the COP trajectory reflects direct posterior shift before turning toward the swing leg. This is unlike either the APA correct condition, in which the COP moves postero-laterally toward the swing foot, or the APA error condition, in which COP moves postero-laterally toward the stance foot first. Our findings coincide with the compromise effect described in decision theory (Busemeyer & Townsend, 1993; Roe et al., 2001; Simonson, 1989), that humans tend to add an alternative that lies between two competing extreme options in the original choice set. With less certain motor preparation, subjects achieved fastest overall stepping among all APA types. This is important because the quickness to initiate a step in response to an environmental perturbation has been shown to be critical for restoring balance and preventing falls (MacKinnon et al., 2007; I Melzer et al., 2007; Itshak Melzer et al., 2007; St George et al., 2007; Uemura et al., 2013). Thus, the cognitive processing that leads to the APA posterior shift should be investigated as it may lead to an optimal strategy for step initiation and fall reduction.

Previous research on the topic of APA error focused on the temporal evolution of GRF under each foot (Cohen et al., 2011; MacKinnon et al., 2007; I Melzer et al., 2007; Itshak Melzer et al., 2007; Uemura et al., 2013). Thus it is possible that the APA posterior shift was not able to be detected as there is no weight redistribution under each foot during COP posterior movement. Another possibility for the non-existence of APA posterior shift in previous research is that previous studies used visual cues as the stimulus. For example, LED cues were used by MacKinnon *et al* (MacKinnon et al., 2007), arrows on a screen were used by Uemura *et al* (Uemura et al., 2013) and Sparto *et al* (Sparto et al., 2014), and laser cues pointing in front of subject's foot were used by Cohen *et al* (Cohen et al., 2011). Whereas we used an auditory cue which was intended to reduce stimulus-response compatibility effects present in these earlier studies which may have reduced uncertainty during the response selection stage in response planning.

The weak positive correlations between sway length and timing in the release and unloading phase indicate that in addition to the coupling of distance and time, cognitive processing also contributes to the delay of the release and unloading phase, as some of the APA PS/Error trials showed subjects' COP freezing during the release and unloading phases. The strong positive correlation between the timing of DSP and its sway path length indicates that the DSP is less affected by cognitive processing, and that the DSP timing is physically bounded by the COP displacement.

Across all test conditions, we found that the duration of DSP in right leg stepping is longer than in left leg stepping. The DSP is the last phase during the step initiation, and the stance limb is responsible for generating the forward momentum to propel the COM to shift forward. It has been reported that the dominant leg generates more energy during plantar-flexion (Dessery, Barbier, Gillet, & Corbeil, 2011; Ounpuu & Winter, 1989), and thus the duration of DSP was prolonged when the stance limb is the non-preferred limb.

5. Conclusion

Our findings suggest that stimulus evaluation during choice reaction step initiation was not completed before movement execution. Instead, the evaluation process continued in the APA phase. Furthermore, the APA posterior shift pattern was identified and its overall step timing indicates a potential advantageous postural adjustment to initiate a fast forward step which could lead to effective training for fall prevention.

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Tables

Table. 1. Summary of the temporal characteristics during step initiation

	SRST, *mean* ± *SD* (ms)	CRST, *mean* ± *SD* (ms)		
		Correct APA	Error APA	PS APA
RT	179.2 ± 55.9	360.5 ± 143.8	264.2 ± 108.5	254.7 ± 109.8
Release	326.3 ± 67.4	325.4 ± 57.3	543.1 ± 135.9	419.9 ± 101.6
Unloading	276.8 ± 41.7	309.1 ± 50.5	300.1 ± 50.7	275.7 ± 45.2
SSP	371.0 ± 71.8	408.9 ± 69.0	336.9 ± 56.6	367.9 ± 70.5
DSP	255.2 ± 79.3	294.0 ± 96.4	270.2 ± 85.1	265.2 ± 74.3
Total	1408.5 ± 195.5	1697.9 ± 229.8	1714.5 ± 254.3	1583.4 ± 235.2

Figures

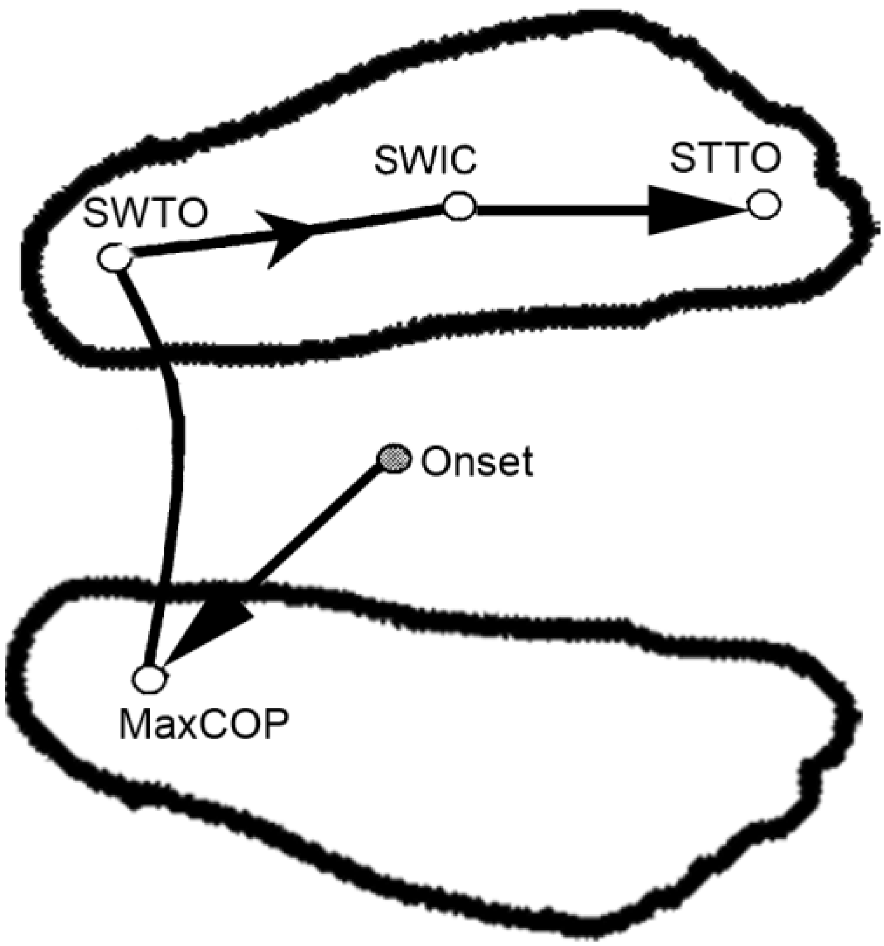

Fig. 1. COP displacement pattern during step initiation. During the release phase the COP moves from onset to the furthest point of posterolateral COP movement (MaxCOP). During the unloading phase the COP moves across from MaxCOP to the stance foot, ending at swing toe off (SWTO). The forward COP displacement from SWTO to stance toe off (STTO) marks the stepping phase (SSP and DSP).

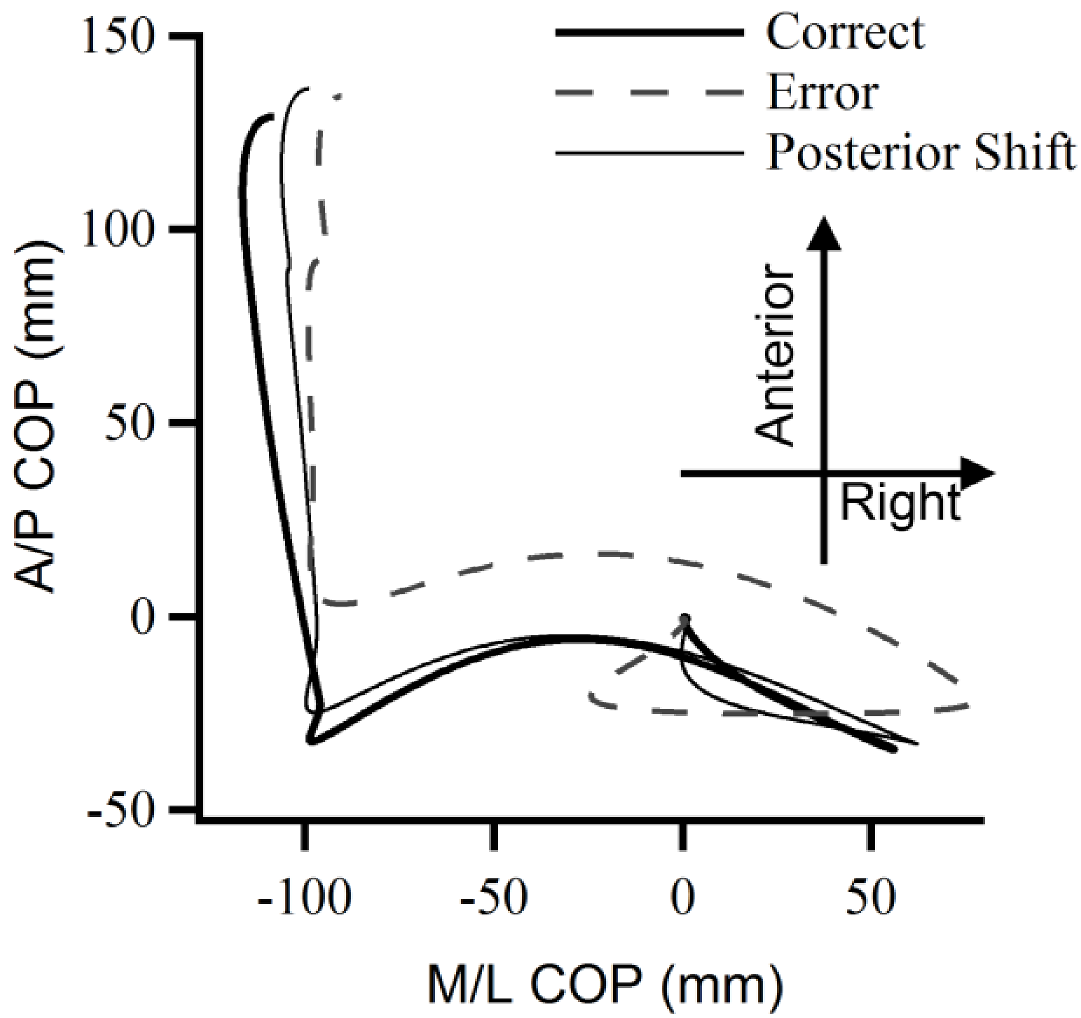

Fig. 2. COP displacement pattern of different APAs during the choice reaction stepping task from one subject. The initial swing limb is the right foot.

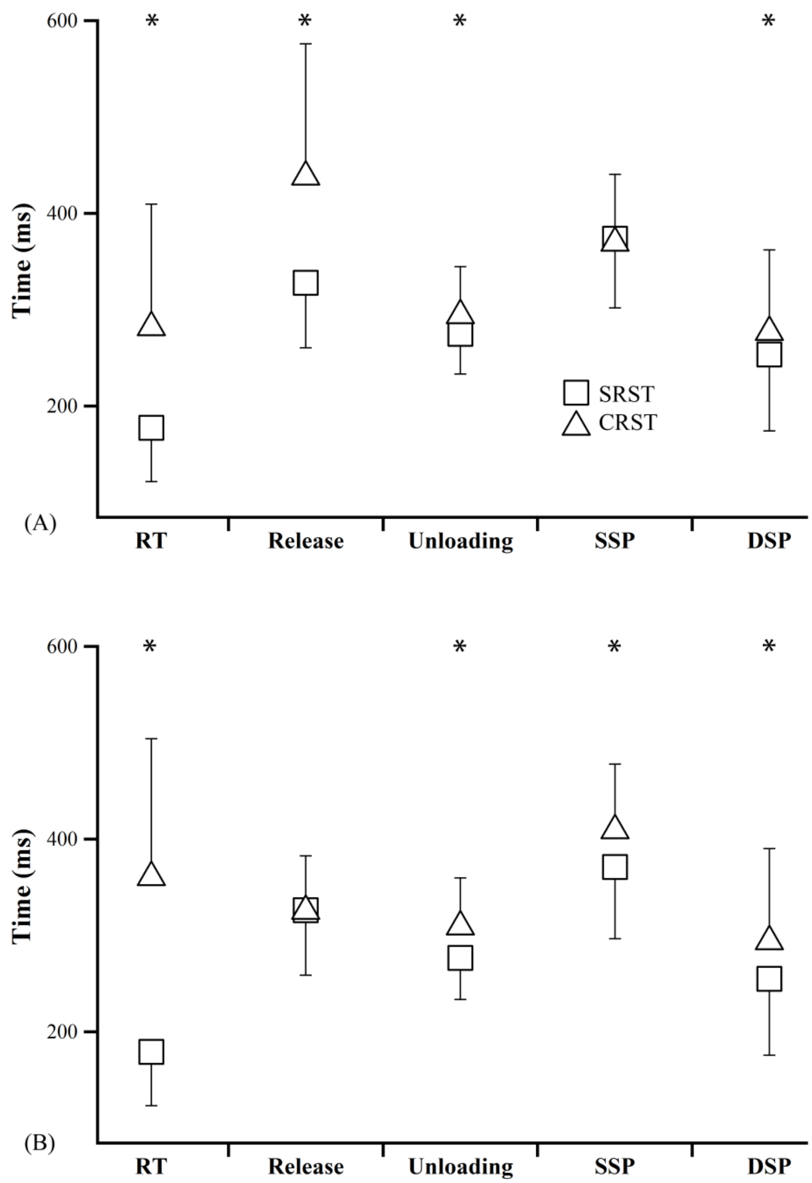

Fig. 3. (A) Effect of stepping task (SRST vs CRST) on temporal characteristic of step initiation. (B) Temporal characteristic of step initiation in trials with correct APAs. Asterisk (*) indicates significant effect of stepping task ($p < .05$). SRST, simple reaction stepping task; CRST, choice reaction stepping task; RT, reaction time; SSP, single support phase; DSP, double support phase. All values represented by mean ± SD.

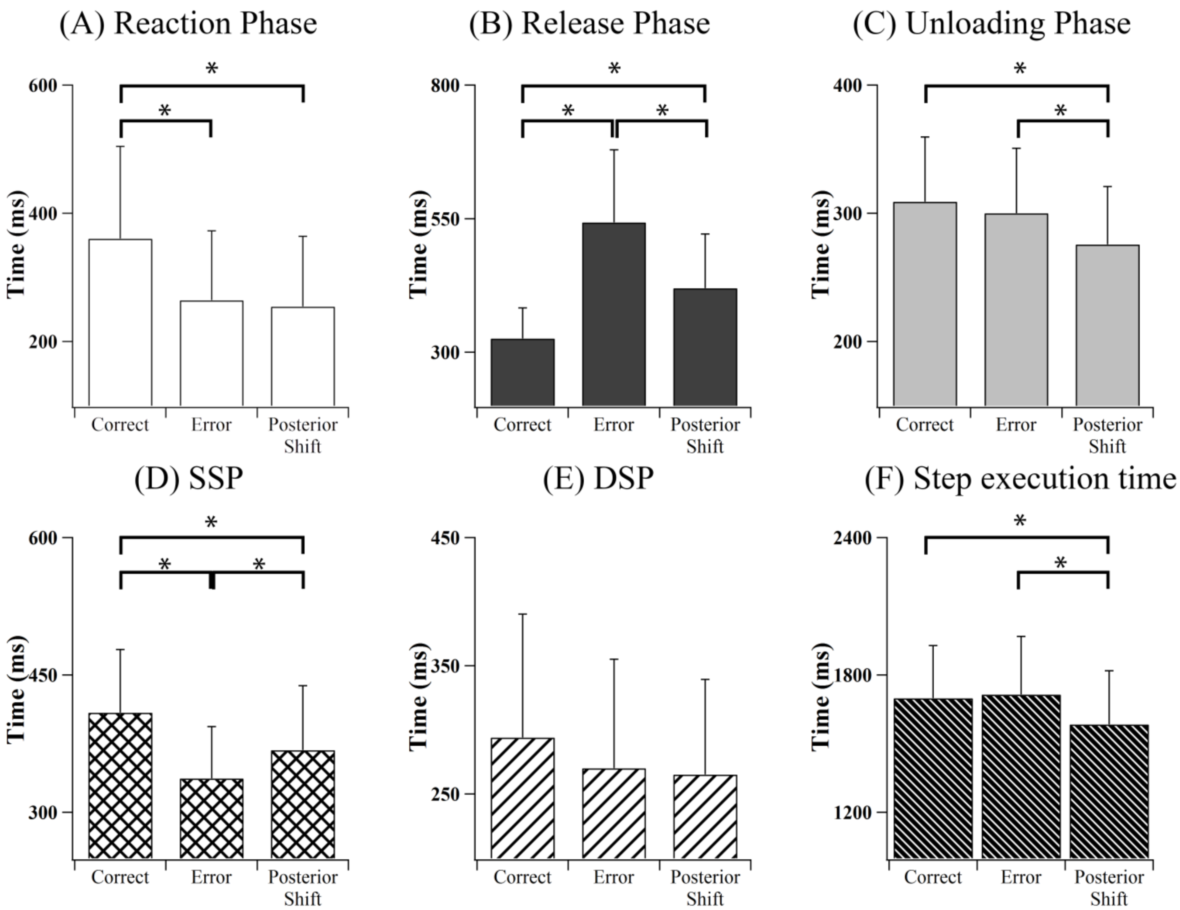

Fig. 4. Duration of temporal characteristic of choice reaction step initiation, (A) reaction time; (B) release phase; (C) unloading phase; (D) single support phase, SSP; (E) double support phase, DSP; (F) total step execution time. Asterisk (*) indicates significant ($p < .05$) difference of group means based on post hoc analysis.