Foreknowledge of postural demands of an upcoming step modulates rapid stepping behaviour

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Abstract

Background: Interacting in a dynamic world often requires reflexive steps. We recently showed in scenarios where stepping introduced low postural demands that rapid steps were facilitated by short-latency (~120 ms) bursts of muscle activity termed express visuomotor responses (EVRs). However, when stepping introduced high postural demands, EVRs were first suppressed, and then mediolateral anticipatory postural adjustments (ML-APAs) were generated. In these prior experiments, participants had certainty that the upcoming step would introduce low or high postural demands. Here, we manipulated such foreknowledge to investigate its influence on EVR and ML-APA expression during step initiation.

Methods: Healthy young adults (n=20) stepped to visual targets over a range of step eccentricities in blocks of foreknowledge present (anterolateral *or* anteromedial steps, involving low or high postural demands) or foreknowledge absent conditions (anterolateral *and* anteromedial steps). We measured bilateral EMG from gluteus medius, vertical ground-reaction forces and step reaction times.

Results: For anterolateral steps, we observed greater EVRs, reduced ML-APAs and shorter reaction times in foreknowledge present vs. absent conditions. Conversely, for anteromedial steps, we observed small EVRs, larger and more ML-APAs and longer RTs under foreknowledge.

Significance: Our results suggest that foreknowledge of low postural demands during anterolateral steps lets people safely launch EVRs while suppressing ML-APAs, prioritizing shorter RTs over balance. In contrast, foreknowledge of high postural demands during anteromedial steps leads people to prioritize balance, expressing ML-APAs and delaying step initiation. Our findings are relevant for individuals with impaired balance control, in whom prioritization of balance may impact rapid stepping.

Introduction

Steps are usually preceded by an anticipatory postural adjustment (APA). The mediolateral component of this adjustment (ML-APA) prevents a loss of balance, engaging *swing*-leg hip abductor muscles (in particular gluteus medius, GM) to direct the center of mass towards the stance limb prior to lifting the foot. The amplitude of this ML-APAs is modulated according to the laterality and speed of the ensuing step [1-4]. Sometimes ML-APAs can be fully absent, such as during protective steps following a balance perturbation [5].

We recently showed that ML-APA are also absent before rapid (average RT ~350 ms) visually-guided anterolateral steps (toward 11.6°) [6]. Intriguingly, robust ML-APAs are typically recruited in other studies under these step eccentricities [1, 4]. In our study with healthy young adults, reflexive steps were performed towards salient and temporally predictable targets, which may have contributed to the abolishment of the ML-APAs. Rather than ML-APAs, in this task, we observed a consistent short-latency (~100 to 140 ms after stimulus onset) burst of *stance*-leg GM activity before anterolateral steps. This burst of activity is the express visuomotor response (EVR) that is thought to be subcortically mediated [7-12] and may aid in rapid stepping, as stronger EVRs precede shorter reaction times (RTs) [6]. The expression of either EVRs or subsequent ML-APAs (~180 ms after stimulus onset) depends on the postural demands of the upcoming steps: when such demands were high, EVRs were greatly attenuated and ML-APAs were strongly present.

In our prior study [6, 13], participants knew the postural demands of the upcoming step in advance (i.e., whether to step anterolaterally from a narrow stance or anteromedially from a wide stance). Such contextual foreknowledge of postural demands (referred hereafter as "foreknowledge" for brevity) differs from the more unpredictable situations in daily life that require rapid stepping, such as rapidly stepping in response to an approaching car.

In the present study, we examined how foreknowledge of postural demands influences the reciprocal relationship between ML-APAs and EVRs. To this end, stepping targets were presented with foreknowledge (where anterolateral or anteromedial targets were presented in separate blocks of trials) or foreknowledge absent conditions (i.e. where anterolateral or anteromedial targets were intermixed within the same blocks of trials). We hypothesized that in the presence of foreknowledge, EVR expression in anterolateral steps would be more pronounced with faster ensuing step RTs, while ML-APA expression would be enhanced in anteromedial steps at the expense of step RTs.

Methods

Participants

A total of 20 young, healthy volunteers (25.2 ± 2.49 years; 14 females, 6 males) participated in this single-session study. Predefined exclusion criteria included a BMI>25 kg/m2 (to ensure EMG signal quality) and self-reported visual, neurological, or musculoskeletal disorders that could affect task performance.

The study was conducted in accordance with the Declaration of Helsinki and approved by the medical ethics committee (CMO Arnhem-Nijmegen, 2023-16109). All participants gave written informed consent and were free to withdraw at any time.

Protocol

Set-up and experimental paradigm

Participants performed a stepping paradigm on a stationary M-gait treadmill (Motek Medical, The Netherlands), on which the task was projected (Optoma, United Kingdom). We recorded vertical ground reaction forces (vGRF) at 2000 Hz using the two embedded force plates. Electromyography (EMG; Wave Wireless EMG, Cometa, Italy) was collected from bilateral GM at 2000 Hz using Ag/AgCl surface electrodes placed according to SENIAM guidelines [14]. For each trial, a photodiode (TSL250R-LF, TAOS, USA) was used to detect the exact moment the step target appeared, allowing for synchronization of force plate and EMG data.

In each trial, participants started with an initial foot position 29 cm apart, as indicated by small circles that were projected onto the treadmill, bearing equal weight between their left and right legs (Figure 1A). A white circular target (15 cm in diameter) appeared in front of the participant and remained stationary for 1000 ms, after which it started to move towards the participant (750 ms) and disappeared behind an occluder (750 ms) while maintaining a similar speed and trajectory. Next, the target reappeared below the occluder for 48 ms in front of the participants' right or left leg, and then vanished. The participant was instructed to step as fast as possible onto the target with the respective leg, place the other leg alongside, and then step back to the initial position. Each participant completed eight blocks of 60 stepping trials. Before starting a block, participants were shown the target positions that could appear in that block. In the *foreknowledge present* condition, anterolateral (14° and 21°) or anteromedial (–9° and –1°) targets were presented in separate blocks of trials, allowing participants to anticipate the general step eccentricity and, hence, the associated postural demand. In contrast, the *foreknowledge absent* condition intermixed both anteromedial and anterolateral targets, preventing participants from anticipating the general step eccentricity. Within a block, targets were presented in a pseudorandomized order such that each location appeared 15 times. The block order was counterbalanced within and across participants.

Data processing

All data preprocessing (EMG, force plate) was performed in MATLAB (Version 2023B, The Mathworks, Inc., USA) using custom-written scripts. Trials were labelled as errors if participants stepped with the incorrect foot, or did not step within 1000 ms after target appearance.

Force plate processing

Stepping reaction time was defined as the interval from target reappearance until the swing leg's vGRF dropped below 1% of body weight (foot-off) [15]. To detect the presence of ML-APAs on a trial-by-trial basis, vGRF signals were first low-pass filtered with a 2^{nd} -order zero-lag Butterworth filter at 50 Hz. We then subtracted the stance leg vGRF from the swing leg vGRF and computed the derivative of this signal, such that a positive value indicates greater forces exerted by the swing leg. We first inspected trials for potential ‘false starts’, defined as premature change-in-forces between the legs in a ‘baseline’ period around target reappearance (i.e. from -100 to 25 ms), using a threshold rate of 200% body weight/second. These trials were labelled as premature weight shifts and excluded from further analysis of EVRs, ML-APAs, or step RTs. With the resulting trials, we calculated a threshold of 5 times the standard deviation of this change-in-force signal within the baseline period. If a trial exceeded this (positive) threshold or fell below the negative threshold within 100 ms following target reappearance, it was also labelled as premature weight shifts. An ML-APA was identified if the change-in-force signal exceeded the threshold (i.e. in the positive direction only) later than 100 ms following target reappearance, and before foot-off. ML-APA latency was defined as the time point of threshold crossing, and ML-APA magnitude was defined as peak swing leg loading from the time point of threshold crossing until foot-off.

EMG data processing

First, stance-leg GM EMG signals were band-pass filtered (20–450 Hz, second-order Butterworth). To detect EVRs on a trial-by-trial basis, we adopted the detrended-integrated method [16]. Briefly, we subtracted the background EMG (–100 to 25 ms relative to target reappearance) signal from the entire EMG recording for that trial, rectified and integrated the resulting EMG signal. Next, we removed any remaining linear trend still present in the baseline period from -100 to +25 ms relative to target reappearance. A detection threshold was calculated of five SDs of the detrended-integrated signal within the baseline period. If a respective EMG signal exceeded this threshold within 90-140 ms following target reappearance, an EVR was deemed present. EVR latency was then determined to be at the intersection with the background EMG level of a linear fit using the last valley and first peak surrounding the threshold crossing. EVR magnitude was calculated as the mean EMG between 100-140 ms, normalized to the participant’s median peak EMG activity of stance-leg GM in the time window of 140 ms following target reappearance to foot-off in the foreknowledge present condition during anterolateral stepping.

Statistics

Statistical analyses and visualization were conducted in RStudio (v2024.12.1). Logistic and linear mixed-effects models were used to examine the effects of foreknowledge condition (present/absent), step eccentricity (–9°, –1°, 14°, 21°), and stepping side (left/right) on step RTs and EVR/ML-APA expression (presence, mean magnitude, median latency), with a random effect for each participant. Data points for each individual condition were only included in the model if ≥3 ML-

APAs/EVRs values were available. Separate models tested whether ML-APA magnitudes and step RTs differed based on EVR presence. With significant *condition × step eccentricity* interactions ($\alpha = .05$), uncorrected post-hoc pairwise comparisons of estimated marginal means were performed to explore the effects of foreknowledge across step eccentricity levels.

Results

Behavioural results

Two participants were excluded from further analysis due to technical difficulties during recording and non-compliance with the protocol.

Participants' error rates were generally low (1.3% over all trials combined; see Figure 2A). However, they made more errors in anteromedial steps (-9° and -1°) compared to anterolateral steps (14° and 21°) (see Table 1 for statistical results), irrespective of foreknowledge condition. The presence of premature weight shifts was differentially modulated by foreknowledge, depending on step eccentricity (step eccentricity x condition, $p < .001$ (Table 1); Figure 2B). Significantly more trials with premature weight shifts were produced during anteromedial steps under presence vs. absence of foreknowledge. In contrast, fewer premature weight shifts were observed during anterolateral steps when foreknowledge was present, as opposed to when it was absent. For further analyses, trials with stepping errors and premature weight shifts were excluded. As a result, an average of 26 trials ($SD = 3.5$) remained per grouped condition (85.5% of all trials).

In these remaining trials, foreknowledge influenced the step RTs in opposite ways for anteromedial and anterolateral steps (step eccentricity x condition, $p < .001$; Figure 2C). In the presence of foreknowledge, participants stepped on average 16 ms earlier in the anterolateral but 13 ms later in the anteromedial direction, as compared to the foreknowledge absent condition.

Effects of step eccentricity and foreknowledge on ML-APA expression

As expected, ML-APAs were expressed less often and with smaller magnitudes before anterolateral vs. anteromedial steps. We observed a weak but opposite influence of foreknowledge on ML-APA presence and magnitudes (step eccentricity x condition, $p \leq .007$; Table 1; Figure 3A and 3B, respectively) across anterolateral and anteromedial steps. During anterolateral steps in the presence vs. absence of foreknowledge, ML-APA presence was significantly lower across both eccentricities, with a significantly smaller ML-APA magnitude at 14°. During anteromedial stepping under foreknowledge, we observed marginally less frequent ML-APAs toward -9°, but larger magnitude ML-APAs toward -1°. No effects of foreknowledge were observed for ML-APA latencies.

Effect of step eccentricity and foreknowledge on EVR expression

EVRs were expressed more often and with a greater magnitude during anterolateral vs. anteromedial steps. Foreknowledge had marginal, yet contrasting effects on EVR presence and magnitudes (step eccentricity x condition, $p \leq .012$; Table 1; Figure 3D and 3E, respectively) for anterolateral versus anteromedial steps. EVRs in the presence of foreknowledge increased for anterolateral targets (increasing in frequency for 14° targets and in magnitude for 21°), but decreased for anteromedial targets (in both frequency and magnitude for -1° anteromedial targets, compared to the absence of foreknowledge. No effects of foreknowledge were observed for EVR latencies.

Effects of EVR presence on ML-APA magnitude and step RTs

We were interested in how the presence or absence of stance-leg EVRs related to the subsequent stepping behaviour. This is particularly relevant for anteromedial steps, since EVRs may inadvertently propel the center of mass outside the prospective base of support. To investigate this, we compared the ML-APA magnitude and step RTs on trials with and without EVRs. When occasional EVRs were present during anteromedial steps, the subsequent ML-APAs were significantly larger than when the EVRs were absent, specifically under foreknowledge (step eccentricity x condition x EVR presence, $p = .024$; Table 1; Figure 4A). This occasional EVR expression was accompanied by longer RTs, but only under foreknowledge (step eccentricity x condition x EVR presence, $p = .017$; Table 1; Figure 4B).

Discussion

In the current study, we investigated how foreknowledge of the postural demand of the upcoming step influences rapid steps in a task that could evoke both EVRs and ML-APAs. We hypothesized that foreknowledge of anterolateral steps results in more pronounced EVR expression, accompanied by shorter step RTs as compared to anterolateral steps in absence of foreknowledge. In contrast, during anteromedial steps in the presence of foreknowledge, ML-APA expression would be enhanced at the expense of step RTs.

Foreknowledge favors reflexive stepping when postural demands are low

Generally, ML-APA expression during anterolateral stepping was low: in less than 50% of trials we observed detectable ML-APAs, and if present, they were marginal in magnitude. In line with our hypothesis, we observed a further shift in favor of reflexive steps with more pronounced EVR expression and shorter step RTs under foreknowledge of low postural demand. This finding is in alignment with prior studies investigating EVR expression in upper limb muscles during reaching movements, which reveal increased EVR expression when task-relevant cues are present, such as instructions [16, 17] or knowledge of the targets' spatial location [7, 18] and timing [19]. Further support is provided by studies that showed RTs also benefit from foreknowledge. For example, participants initiate eye and hand responses earlier in blocks where targets jumped on every trial, compared to blocks of occasional target jumps [20]. Together, these results suggest an increased readiness for the generation of fast goal-directed movements under task-relevant foreknowledge.

Foreknowledge favors postural control at the expense of step initiation when postural demands are high

In contrast, anteromedial steps in the presence vs. absence of foreknowledge yielded marginally smaller EVR magnitudes, larger ML-APA magnitudes and delayed step RTs compared to steps in absence of foreknowledge. Together, these results point towards a limited prioritization of posture at the expense of stepping RT under foreknowledge of high postural demand, and reinforce that adopting a 'posture-first' strategy does not facilitate step initiation. This notion agrees with prior research revealing longer RTs of goal-directed focal movements under more challenging balance demands [21] or in the expectance of an upcoming postural perturbation [22, 23]. Furthermore, another study on arm-body coordination found longer RTs for the focal arm movement correction, yet with shorter RTs for the postural responses in trials where target jump direction was predictable (vs. unpredictable) [24]. Thus, this suggests that prioritization of posture may not always be helpful in certain components of task performance. Indeed, in anteromedial trials where EVRs were occasionally expressed, this was followed by larger compensatory ML-APAs and longer step RT when foreknowledge was present vs. absent, even though EVR magnitudes were comparatively smaller. Together, these results suggest that postural prioritization leads to greater correction for potential kinetic consequences of the occasional EVR expression, complementing findings of our previous study [6].

Furthermore, during anteromedial steps under foreknowledge, participants displayed more frequent, premature and non-target selective weight shifts compared to all other conditions, which can be seen as 'false starts' with a 50% probability of initiating the step in the wrong direction. In case of a premature weight shift in the wrong direction, a compensatory second APA will be needed to allow a stable anteromedial step with the correct leg. This inherently delays step RT [25] or it may potentially lead to the wrong leg initiating the step if the incorrect weight shift is not aborted. Conversely, foreknowledge of low postural demands led to very infrequent premature weight shifts, suggesting that the findings at the anteromedial eccentricities are indeed related to the participants preparing for ML-APA execution [25, 26]. This concurs with our previous EEG work, where participants showed preparatory motor cortical activity under foreknowledge of an upcoming anteromedial step [13]. In daily life, the presence of such premature weight shifts may not pose a problem, or it may even benefit step RTs, when the task at hand does not constrain the stepping leg. However, problems may potentially arise if, for instance, one leg is obstructed.

Clinical implication

In the current study, we observed that foreknowledge of low postural demands results in prioritization of faster step initiation. However, the ability to prioritize rapid goal-directed step initiation may be compounded by an individual's perceived balance capacity: if one's balance capacity is affected due to ageing or disease, this likely translates to a relatively greater postural demand of the task, and thus an overall lower propensity of reflexive step initiation. Indeed, we recently found that healthy elderly as well as people with Parkinson's Disease – both groups likely having poorer balance capacity than the young participants in the present study – demonstrated comparatively low-magnitude EVRs and larger magnitude ML-APAs when stepping anterolaterally under foreknowledge [27]. While these observations may indeed suggest a more conservative stepping strategy in these populations, their slower stepping speeds may also necessitate greater ML-APAs expression to compensate for the prolonged 'falling' time of the CoM during the longer-lasting single stance phase of the ensuing step [3]. It remains to be established whether these postural factors underlie the observed attenuation of EVRs and consequent delay in step RTs in these populations. Alternatively, the EVR network itself may also degrade with ageing, as previously speculated in our recent preprint [28]. It should be noted that although postural prioritization may counteract reflexive stepping, it is a useful strategy in situations involving more challenging balance demands.

Conclusion

We have shown that foreknowledge of low postural demand results in prioritization of step initiation enhancing EVRs and suppressing ML-APAs. Conversely, with foreknowledge of high postural demand, participants displayed a limited prioritization of ML-APA recruitment at the expense step initiation. If occasional EVRs were expressed during anteromedial steps, this resulted in larger compensatory ML-APAs and longer step RTs, particularly under foreknowledge. These findings may be important for individuals with impaired balance control, as prioritization of postural control may impact rapid stepping.

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Contributions

IG: Funding acquisition, Data curation, Investigation, Methodology, Formal analysis, Visualization, Writing – Original draft; **BDC:** Validation, Writing – Review and editing; **WPM:** Validation, Supervision, Writing – Review and editing; **VW:** Conceptualization, Methodology, Writing – Review and editing, Validation, Supervision, Project administration.

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Table 1. Statistical results of main- and interaction effects.

	Outcome	Effects	Statistics	Post-hoc pairwise comparison		P-value
Behavioural results	Errors	*Step eccentricity*	$\chi^2(3) = 71.11$, $p < .001$			
	Premature ML-APAs	*Step eccentricity × condition*	$\chi^2(3) = 76.58$, $p < .001$	Foreknowledge present versus absent		**-9°: $p < .001$** **-1°: $p < .001$** **14°: $p < .001$** **21°: $p = .034$**
	Step RTs	*Step eccentricity × condition*	$F(3, 259) = 5.71$, $p < .001$	Foreknowledge present versus absent		**-9°: $p = .026$** **-1°: $p = .049$** **14°: $p = .015$** 21°: $p = .136$
ML-APA	Presence	*Step eccentricity x condition*	$\chi^2(3) = 17.50$, $p < .001$	Foreknowledge present versus absent		**-9°: p = .014** -1°: p = .477 **14°: $p < .001$** **21°: $p < .001$**
	Magnitude	*Step eccentricity x condition*	$F(3, 234.18) = 4.16$, $p = .007$	Foreknowledge present versus absent		-9°: p = .820 **-1°: p = .020** **14°: p = .014** 21°: $p = .362$
	Latency	*Step eccentricity*	$F(3, 238.15) = 5.88$, $p < .001$			
EVR	Presence	*Step eccentricity x condition*	$\chi^2(3) = 18.7$, $p < .001$	Foreknowledge present versus absent		-9°: $p = .786$ - 1°: $p = .053$ **14°: $p < .001$** 21°: $p = .072$
	Magnitude	*Step eccentricity x condition*	$F(3, 255) = 3.72$, $p = .012$	Foreknowledge present versus absent		-9°: $p = .555$ - **1°: $p = .034$** 14°: $p = .154$ **21°: $p = .019$**
	Latency					
EVR presence	Step RTs	*Step eccentricity x condition x EVR presence*	$F(3,533) = 3.42$, $p = .017$	EVR present versus absent	Fore-knowledge present:	**-9°: $p = .003$** -1°: $p = .065$ **14°: $p < .001$** **21°: $p < .001$**
					Fore-knowledge absent:	-9°: p = .553 -1°: p = .116 **14°: $p = .030$** **21°: $p = .002$**
	ML-APA magnitude	*Step eccentricity x condition x EVR presence*	$F(3,484.04) = 3.19$, $p = .024$	EVR present versus absent	Fore-knowledge present:	**–9°: $p < .001$;** **–1°: p < .001;** 14°: $p = .538$ 21°: $p = .796$
					Fore-knowledge absent:	**–9°: $p < .001$;** **–1°: p < .001;** **14°: $p = .034$** 21°: $p = .338$

Note. The table displays the main effects, interaction effects, and post-hoc pairwise comparisons for the significant eccentricity × condition interaction. Significant differences between conditions in the uncorrected post-hoc comparisons are highlighted in bold.

Figure captions

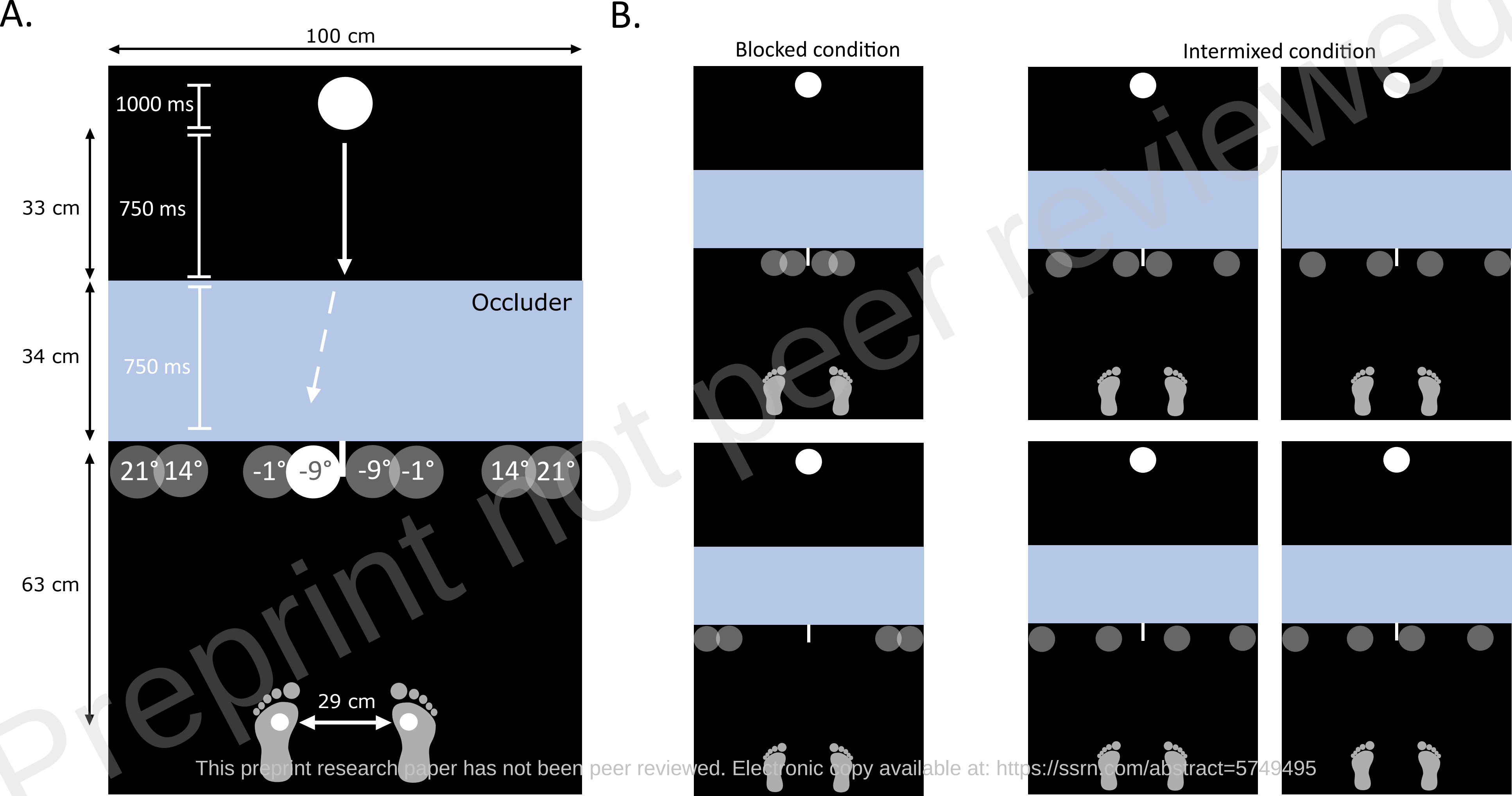
Figure 1. A. *Experimental set-up with all possible step eccentricities. Initially, the feet were placed 29 cm apart. When a trial was started, a white, circular target appeared and remained stationary for 1000 ms, after which it started to move towards an occluder (750 ms), disappeared behind it (750 ms) while retaining its speed and reappeared in front of the participant's left or right leg.* **B***. The foreknowledge present condition consisted of solely anteromedial (5 and 13 cm from midline) or*

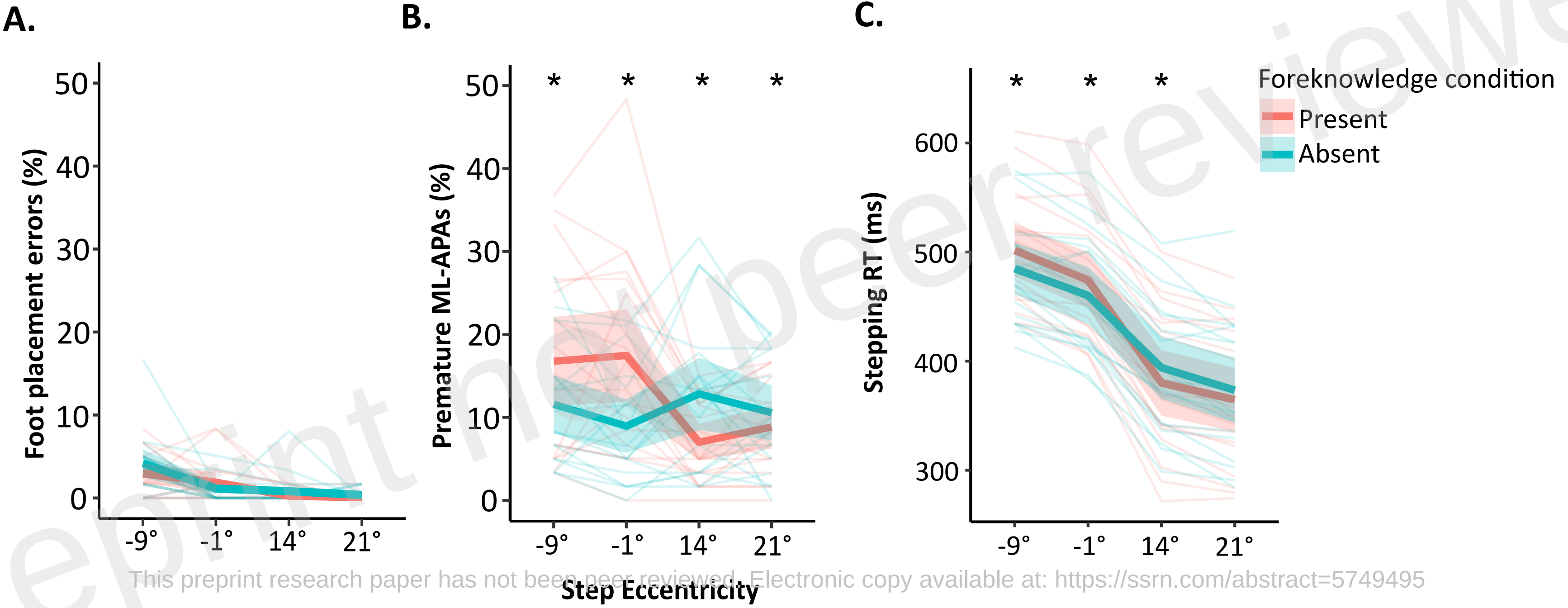
anterolateral targets (31 and 39 cm from midline). The foreknowledge absent condition consisted of intermixed anteromedial and anterolateral stepping targets. Target eccentricities in panels of panel B reflect those indicated in panel A.

Figure 2: A. *Percentage of step errors as a function of step eccentricity, with the foreknowledge absent condition shown in blue and the foreknowledge present condition in red. Thinner lines indicate individual participant means* **B.** *Percentage of trials with premature weight shifts.* **C**. *Step RTs.*

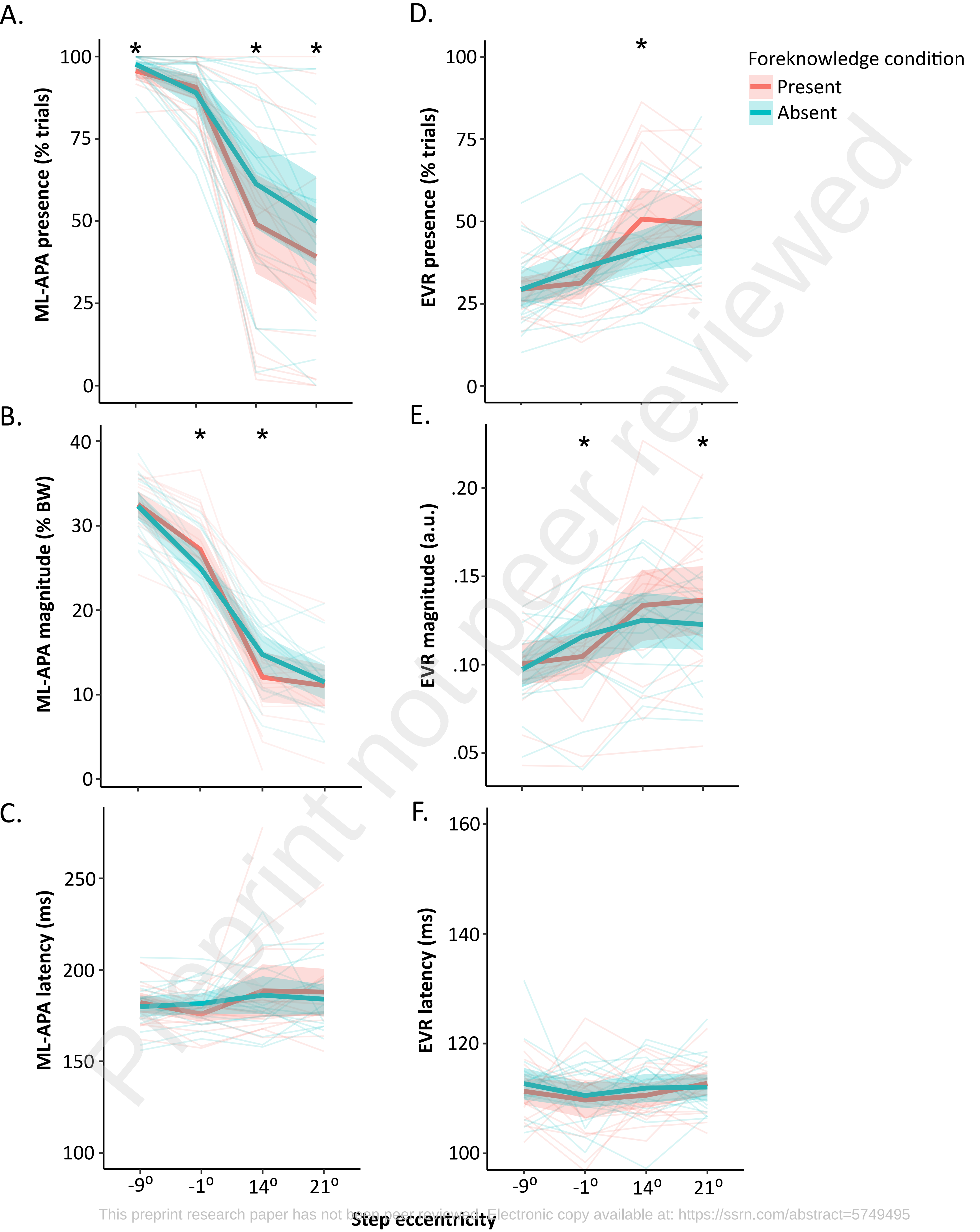
Figure 3: *EVR/ML-APA expression as a function of step eccentricity, with the foreknowledge absent condition shown in blue and the foreknowledge present condition in red. Thinner lines indicate individual participant means.* **A.** *ML-APA presence* ***B.*** *ML-APA magnitude* **C.** *ML-APA latency* **D.** *EVR presence* **E.** *EVR magnitude* **F.** *EVR latency*

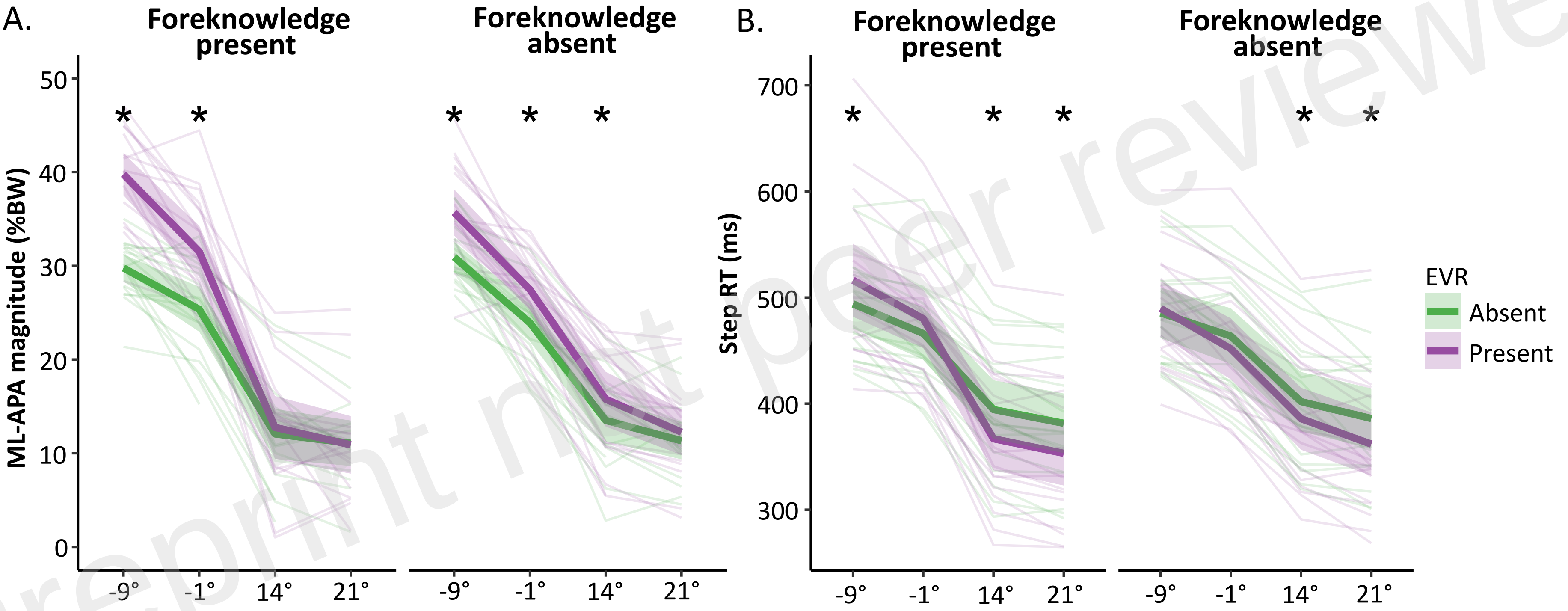
Figure 4. A. *ML-APA magnitudes in % bodyweight when EVRs were present (purple) or absent (green) for the foreknowledge present (left) and foreknowledge absent (right) condition. Shaded bands represent 95% confidence intervals, and thinner lines indicate individual participant means.* **B.** *Step RTs (in ms) for when EVRs were present (purple) or absent (purple) for the foreknowledge present (left) and foreknowledge absent (right) condition.*


A.
100 cm
1000 ms
33 cm
750 ms
34 cm
750 ms
Occluder
21°
14°
-1°
-9°
-9°
-1°
14°
21°
63 cm
29 cm
B.
Blocked condition
Intermixed condition



A.
B.
C.
Foot placement errors (%)
Premature ML-APAs (%)
Stepping RT (ms)
50
40
30
20
10
0
600
500
400
300
*
-9°
-1°
14°
21°
Step Eccentricity
Foreknowledge condition
Present
Absent


A.
B.
C.
D.
E.
F.
ML-APA presence (% trials)
ML-APA magnitude (% BW)
ML-APA latency (ms)
EVR presence (% trials)
EVR magnitude (a.u.)
EVR latency (ms)
Foreknowledge condition
Present
Absent
-9º
-1º
14º
21º
Step eccentricity



A.
Foreknowledge present
Foreknowledge absent
ML-APA magnitude (%BW)
0
10
20
30
40
50
-9°
-1°
14°
21°
B.
Foreknowledge present
Foreknowledge absent
Step RT (ms)
300
400
500
600
700
EVR
Absent
Present