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Dynamic postural control during (in)visible curb descent at fast versus comfortable walking velocity

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Highlights

- No interaction between walking velocity, curb elevation and visibility on MoS
- No walking velocity effect of curb type on MoS in the first recovery step
- Lower dynamic postural stability in both descent and recovery from a camouflaged curb
- Walking faster led to a decreased MoS in both camouflaged and visible curb conditions

Abstract

Background: The unexpectedness of ground-contact onset in stepping down due, e.g., to a camouflaged curb during ongoing gait may impose potential postural control challenges, which might be deteriorated when walking faster.

Research question: Does traversing camouflaged versus visible curbs, at a fast walking velocity, induce more unstable body configurations, assessed by a smaller anteroposterior "margin of stability" (MoS)?

Methods: For twelve healthy participants, we investigated MoS at foot touchdown in descent and in the first recovery step from 0- and 10-cm visible and camouflaged curbs at comfortable (1.22 ± 0.08 m/s) and fast (1.71 ± 0.11 m/s) walking velocities. Three-way (velocity, elevation, visibility) and two-way (velocity, visibility) repeated-measurement ANOVAs were performed to determine their interactions on MoS, and its determining parameters, during curb negotiation and recovery step, respectively.

Results: No greater postural instability when traversing a camouflaged versus visible curb at a faster walking velocity during curb descent, indicated by no three-way interaction effects on MoS. However, an elevation-by-visibility interaction showed a dramatic decrease of MoS when descending a 10-cm camouflaged versus visible curb. This was because of a farther anterior displacement of center-of-mass with a larger velocity. Furthermore, the walking velocity was independently associated with a smaller MoS and a more anteriorly-shifted center-of-mass with a higher velocity. In the recovery step, participants demonstrated a reduced stability of the body configuration when walking faster or recovering from a camouflaged than from a visible curb. The

mentioned result implies that the potential to increase the base-of-support to compensate for an increased center-of-mass velocity, induced by an increased walking velocity, is limited.

Significance: Despite a significant independent main effect of walking velocity, a more unstable postural control observed during traversing of camouflaged versus visible curbs was found not to be walking velocity-related in young individuals. Further research, including elderly may shed more light on these results.

Keywords: Uneven walking; Curb negotiation; Velocity; Margin of stability; Postural control

1. Introduction

The occurrence of unexpected perturbations to the gait pattern, arising e.g. from an unexpected curb, is very common in both indoor and outdoor environments. Errors in foot placement in the last step prior to the curb may result in a misstep on the curb, and thus approach performance is fundamental for safety [1]. Healthy, young adults have been found to accommodate both ascent and descent of visible curbs with ease through an accurate adjustment to step length during the approach to the curb, irrespective to the walking velocity [2]. Nevertheless, stepping on an uneven surface is one of the potential threats to dynamic stability in older adults [3, 4] and neuropathy patients [5]. Successful curb descent, thus, requires not only the proper modulation of the foot placement prior to the curb-edge [2, 6], but the adaptations in the gait pattern according to the physical characteristics of the curb to ensure a safe and smooth transition during ongoing locomotion.

Vision is the primary sensory source for the modulation of the walking path and pattern in navigating natural or artificial settings [7]. Being aware of an obstacle in ongoing walking, pedestrians tend to decelerate by reducing step length in order to facilitate stepping over the obstacle [2, 8]. Chen et al. (1994) [9] suggest that young adults often adjust stepping pattern in the last two steps leading up to the obstacle, whereas older adults require an additional step. Previous other perturbation experiments have reported the potential effects of the foresight from the lower visual field [10, 11], the ambient lighting [12] and the visual unawareness of changes in the ground surface [13-17] on the online control of gait adaptation. Lack of or inadequate visual awareness of changes in ground surface during ambulation may pose potential threats to dynamic postural control. Müller et al. (2014) [13] confirmed the significance of visual perception of external perturbations on the global walking pattern during crossing camouflaged drops in ground surface.

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van Dieën et al. (2007) [14] suggested that a quick reactive response by trailing limb when crossing an unexpected descent in ongoing walking is a responsible fall-avoidance strategy in young adults. They assumed that an inefficiency in implementation of such strategy may lead to fall in the elderly. While these investigations have examined balance control in an obstructed gait based on either kinematic and kinetic adaptations or body momentum at normal walking velocity, considering the behavior of the whole-body center-of-mass (CoM) in relation to the stepping pattern, and the impact of velocity on dynamic postural control warrant further research.

The control of dynamic stability may be conceived as a key motor priority in human bipedal locomotion, since the CoM falls outside of the base-of-support (BoS) during ~80% of the gait cycle [18]. Unlike the standing balance, dynamic stability is challenged by the moving nature of both the BoS and CoM at different walking velocities as well as by changing-size of the BoS [19]. As an individual outcome measure, the margin of stability (MoS) [20] allows a step-to-step quantitative analysis of dynamic control of stability by considering the CoM position and its velocity (i.e., extrapolated CoM; X_{CoM}) with respect to the BoS. In theory, a smaller or negative difference between the BoS and X_{CoM} during gait indicates a less stable body configuration which may require the execution of compensatory postural and/or motor responses to maintain dynamic stability.

The magnitude of the MoS is substantially influenced by walking velocity because it increases forward CoM velocity [21]. It comes as no surprise that increasing walking velocity has been associated with lower stability at foot touchdown [22, 23]. At faster walking velocities, the attenuation of unexpected perturbations demands more rapid neuromuscular responses [24]. Moreover, the earlier findings support the notion of method-specific predictive and reactive responses to experimentally-induced perturbations to gait pattern. For instance, a higher anterior velocity of the CoM appears to benefit the recovery from a slippery surface [25, 26], whereas such strategy may increase fall risk following tripping [27]. To date, no research has specifically focused on the negotiation of a camouflaged curb at different walking velocities. Such investigation can provide insight into underlying mechanisms responsible for dynamic postural control during perturbed gait. Thus, our study aimed to compare dynamic postural control in descending and recovering from visible and camouflaged curbs with that of unobstructed walking at two velocities: comfortable and fast. Given the unexpectedness of the ground-contact onset in stepping down under a camouflaged curb, we hypothesized that crossing camouflaged versus visible curbs at a

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faster than at a comfortable walking velocity would result in more unstable body configurations, described by a decreased MoS, in both descending and recovering from a 10-cm camouflaged versus visible curb, as the X_{CoM} would exceed the BoS due to a farther and faster CoM travel in walking direction.

2. Methods

2.1. Participants and experimental design

A convenience sample of twelve healthy, physically active volunteers (3 female, 9 male; mean ± S.D.; age = 25.5 ± 4.7 years, mass = 68.8 ± 8.0 kg, height = 179.1 ± 9.0 cm) gave informed consent and participated in the study. The experimental protocol was approved by the local Ethics Committee of Friedrich-Schiller-University Jena (3532-08/12) and conducted according to the Declaration of Helsinki. Prior to data collection, each participant underwent sufficient practice trials, ensuring that the first forceplate was struck with left foot while walking at two velocities: comfortable (1.22 ± 0.08 m/s) and fast (1.71 ± 0.11 m/s). Gait velocity was calculated as the average horizontal velocity of the CoM during a stride taken by the left foot over the curb. Participants, first, completed eight successful trials per visible curb conditions, comprising a 0-cm (VC0; unobstructed track) and a 10-cm visible curbs (VC10). The latter one was created by lowering the second forceplate by 10-cm (Fig. 1). Visible curbs and velocity were block randomized. To reduce the anticipation of the perturbation onset, participants negotiated ten camouflaged curbs at comfortable and fast walking velocities, where the lowered second forceplate (−10-cm) was camouflaged by a wooden either solid (CC0, 0-cm camouflaged curb) or a hollow (CC10, 10-cm camouflaged curb) forceplate-size box. The boxes were covered by a non-transparent thin paper (Fig. 1). Participants had to accomplish ten successful trials (6 × CC0 and 4 × CC10) with the camouflaged curb occurrence being randomized. Trials were considered successful when each single force plate was fully struck by one foot during walking conditions without losing any reflective markers.

2.2. Assessment of dynamic stability control during curb descending

All participants were instructed to walk along an 8-m, custom-built track with two consecutive forceplates embedded in its center. To create a descent during ongoing walking, the track was lowered from the site of the second forceplate (960 Hz; Kistler, Switzerland) by 0- and 10-cm, while the elevation of the first forceplate (960 Hz; Kistler, Switzerland) was set in flush with the

surface of the first-half of the track (Fig. 1). Kinematic data was collected using eight infra-red motion capture cameras (240 Hz; MCU1000, Qualisys, Sweden). An eleven-body segment model was defined using eighteen 19-mm retro-reflective markers, placed on the tip of the fifth toe, lateral malleolus, epicondylus lateralis femoris, trochanter major, anterior superior iliac spine, acromion, epicondylus lateralis humeri and ulnar styloid proc. on both sides of the body as well as on L5 and C7 processus spinosus. Kinetic and kinematic data were analyzed using custom written Matlab code (R2017a; Mathworks). Marker trajectories data were filtered using a bidirectional, fourth-order, low-pass Butterworth-Filter with a cutoff frequency of 12 Hz. The whole-body CoM was calculated using body segment inertial parameters [28]. The instant of foot touchdown and toe-off during the first and second ground contacts were determined using a vertical GRF threshold of 0.02 body-weight. For the recovery step, there was no GRF available and, therefore, the instant of foot touchdown was determined by the velocity profile of the foot markers [29]. The anteroposterior MoS at foot touchdown was calculated as the difference between the anterior boundary of the BoS and the extrapolated CoM ([20]; for details, see Fig. 1).

2.3. Statistics

The mean values of MoS and its determining parameters (BoS, CoM position, CoM velocity and w_0; Fig. 1) were calculated across trials for each walking velocity, curb type and subject. For normally distributed data sets, we examined velocity- (comfortable and fast), elevation- (0- and 10-cm) and curb visibility-related (visible and camouflaged) effects on MoS and its determining parameters during curb descent, using three-way repeated-measurement ANOVAs. Unlike VC0, VC10 and CC10, the post-perturbation step under CC0 condition followed by a stepdown which represents an inconsistency compared with the rest of walking conditions. Therefore, we performed two-way repeated-measurement ANOVAs to explore the velocity (comfortable and fast) and curb (VC0, VC10 and CC10) related effects on MoS and its determining parameters in the first post-perturbation step (recovery step). Bonferroni post-hoc multiple tests were performed for multiple comparisons. All statistical analyses were conducted using SPSS 23.0 (SPSS, Inc., Chicago, IL, USA). The significance level was $\alpha = 0.05$. Results are presented as mean and standard deviation.

3. Results

3.1. Locomotor control during curb descending

ANOVA revealed no velocity × elevation × visibility interaction on MoS ($F_{1,10} = 3.01$, $p = 0.11$), and on the parameters that contributed to the MoS calculation ($p > 0.05$), indicating that the variations in MoS and its contributing parameters due to descent from 10-cm (in)visible curbs were not walking velocity dependent. However, significant elevation × visibility interactions were detected for MoS ($F_{1,10} = 167$, $p < 0.0001$), CoM position ($F_{1,10} = 541$, $p < 0.0001$) and CoM velocity ($F_{1,10} = 70.5$, $p < 0.0001$) as well as a velocity × visibility interaction for the BoS ($F_{1,10} = 12.2$, $p = 0.006$). In CC10 versus each of other three walking conditions, *post-hoc* comparisons revealed a significant decrease of MoS ($p < 0.0001$; Fig. 2A), and a significant increase in CoM position ($p < 0.0001$; Fig. 2B) and velocity ($p < 0.001$; Fig. 2C). The same trend was observed in VC10 versus both VC0 and CC0 ($p < 0.0001$), except for the CoM velocity ($p > 0.05$). Further *post-hoc* comparisons revealed a significantly larger BoS at a fast than at a comfortable walking velocity during negotiating both visible and camouflaged curbs, and during 10- versus 0-cm curb descending ($p < 0.001$; Fig. 2D). For velocity main effect, a faster than a comfortable walking velocity was significantly associated with a smaller MoS and a more anteriorly-shifted CoM with a larger velocity ($p < 0.001$; Figs. 2A, B and C). No significant between-curb differences were found in $\sqrt{g/l}$ term at both walking velocities ($p > 0.05$).

3.2. Locomotor control in the first post-perturbation step (recovery step)

The velocity × curb interaction on MoS was insignificant ($F_{2,20} = 1.78$, $p = 0.19$), indicating that the recovery of stability from 10-cm in(visible) curbs in the recovery step is not walking velocity dependent. However, ANOVA confirmed significant main effects of velocity ($F_{1,10} = 311$, $p < 0.0001$) and curb ($F_{1.24,12.4} = 25.4$, $p < 0.0001$) on MoS. The MoS was significantly smaller at fast versus comfortable walking velocity ($p < 0.0001$; Fig. 3B). For curb effect, MoS demonstrated a significant decrease in recovery from CC10 versus both 0- and 10-cm visible curbs ($p < 0.05$; Fig. 3B). For parameters contributing to the MoS calculation, there was only a significant velocity × curb interaction for the CoM position ($F_{2,20} = 6.32$, $p = 0.007$). *Post-hoc* comparisons revealed a greater forward shift in the CoM position in recovery from CC10 compared with both 0- and 10-cm visible curbs at both walking velocities ($p < 0.05$; Fig. 3A). Furthermore, the CoM position demonstrated a significant forward shift at a fast versus comfortable walking velocity across all

curb conditions ($p < 0.05$; Fig. 3A). Significant independent main effects of velocity ($p < 0.0001$; Figs. 2C and D) and curb ($p < 0.0001$; Figs. 2C and D) were detected for BoS and CoM velocity. The magnitude of both parameters was greater at a fast versus comfortable walking velocity ($p < 0.0001$; Figs. 2C and D). Between-curb comparisons showed a significantly greater BoS in recovery from CC10 than from both 0- and 10-cm visible curbs ($p < 0.0001$; Fig. 3C), and in 10- versus 0-cm visible curb ($p = 0.002$; Fig. 3C). The CoM velocity was higher in recovery from CC10 compared with both 0- and 10-cm visible curbs ($p < 0.006$; Fig. 3D). $\sqrt{g/l}$ term did not significantly change across recovery from walking conditions at both walking velocities ($p > 0.05$). The full statistical results can be found in the supplementary material.

4. Discussion

In this study, we investigated the anteroposterior margin of stability (MoS) during uneven walking at comfortable and fast walking velocities. In contrast to our hypothesis, a faster than a comfortable walking velocity did not induce more unstable body configurations (i.e. a smaller MoS) in both descent and recovery from a camouflaged (CC10) versus visible curb (VC10). However, the walking velocity was independently associated with a smaller MoS and a more anteriorly-shifted CoM with a higher velocity. Moreover, a camouflaged versus visible curb descent resulted in a more unstable configuration. This was due mainly to a farther CoM forward displacement with a larger velocity. In the recovery step, the effects of curb type on MoS was not found to be velocity-related. However, participants demonstrated a reduced stability of the body configuration when walking faster (velocity main effect) or recovering from a camouflaged curb than from visible curbs (curb main effect). These findings highlight the effect of a higher walking velocity on stability of the body configuration, and the negative impact of an unexpected perturbation onset on the global postural control during curb descent in ongoing walking.

Pre-adaptations in locomotor behavior driven by a feedforward control (i.e. the visual information), may have helped participants to attenuate the impact of a visible curb on dynamic postural control, regardless of walking velocity. Although known ground-level differences caused changes in the CoM state compared with level walking, an unexpected ground-contact onset was associated with a more pronounced CoM forward displacement with a larger velocity than when performing an expected stepdown. A faster walking velocity resulted in a larger BoS under both visible and camouflaged curb descents, but the curb expectedness did not significantly change the

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BoS between camouflaged versus visible curb descent at both comfortable and fast walking velocities. The missteps due to a trip, slip, or loss of balance may induce perturbations to the gait pattern, which, if are not compensated for by timely, appropriate, reactive recovery responses, then the likelihood of a stumble or fall increases. van Dieën et al. (2007) [14] found that the time discrepancy of 110-ms between expected and actual ground-contact in 10-cm stepdown can limit the adjustments in step length and global kinematics, which, in turn, reduces capacity to counter both forward horizontal and angular momenta. In another study [13], an observation of substantial compensatory kinematic and kinetic adjustment when accommodating unexpected versus expected drops in ongoing walking were explained by inadequate preparations in locomotor system, stemmed from the unawareness of the perturbation. In agreement with the results of above studies, our findings illustrate how the unexpectedness of a curb in ongoing walking can impose greater postural stability challenges.

We identified an independent influence of walking velocity on MoS in the recovery step as such in the perturbed step. This finding corroborates previous studies [21-23, 25] illustrating sensitivity of global dynamic gait stability to walking velocity, particularly when observing an increased falling risk following tripping with faster velocities [24]. The CoM position was further forward in recovery from a camouflaged than from both visible 0- and 10-cm curb descents. This was due to a larger perturbation stimulus (i.e., unexpected ground-contact) with a more pronounced increase at a faster walking. Such a significant forward shift may be attributed to the larger forward momentum of the body at foot touchdown which is likely caused by an impaired control of the trunk segment, given its largest contribution to the total body mass (nearly two-third). Interestingly, the largest size of the BoS appeared in post-perturbation step following a camouflaged curb, but yet inadequate to provide a larger margin for the extrapolated CoM. This might be because of the farther and faster CoM travel at foot touchdown when recovering from a camouflaged curb. The ability of providing such a greater margin for the stability would possibly imply swift step-to-step adaptations and plasticity in able-bodied gait. A less favorable reactive recovery responses following a camouflaged curb is owing to the unexpectedness of the perturbation onset that possibly precluded adequate proactive and adaptive adjustments in locomotor behavior. When accommodating a visible curb, participants may, in contrast, have benefited from a greater temporal margin, thereby capable of generating adequate joint moments to resist extensive CoM velocity.

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There are a few limitations to our study that warrant a brief discussion. First, our experimental setup did not permit further analysis of the subsequent recovery steps. Second, we investigated only a 10-cm curb. Further studies are required to characterize dynamic postural control under larger lowered (in)visible elevations. Third, the generalization of our results to other populations e.g. older adults should be treated with caution, as they more likely to fall under a more complex daily ambulation due to a decline in neuromuscular and sensorimotor systems. However, the elderly versus young adults are expected to exhibit a more impaired postural control when encountering (in)visible curbs, particularly at a faster walking velocity. Furthermore, our findings might be influenced by higher type-one error rates due to the multiplicity inherent in the exploratory multiway ANOVA and thus likely less compelling than presented. We also acknowledge a restricted generalizability of the observed dynamic postural control since our protocol did not represent an entirely unexpected, real-life curb negotiation.

5. Conclusion

Despite a significant independent main effect of walking velocity, a more unstable postural control following a camouflaged versus visible curb accommodation was observed not to be walking velocity-related in young, healthy individuals. These findings confirm previous studies explaining underlying challenges associated with dynamic postural control during uneven locomotion, particularly when walking is affected by both or either of the unexpected onset of perturbation and a higher velocity. Further research, including elderly may shed more light on these results.

Conflict of interest statement

The authors declare no conflicts of interest.

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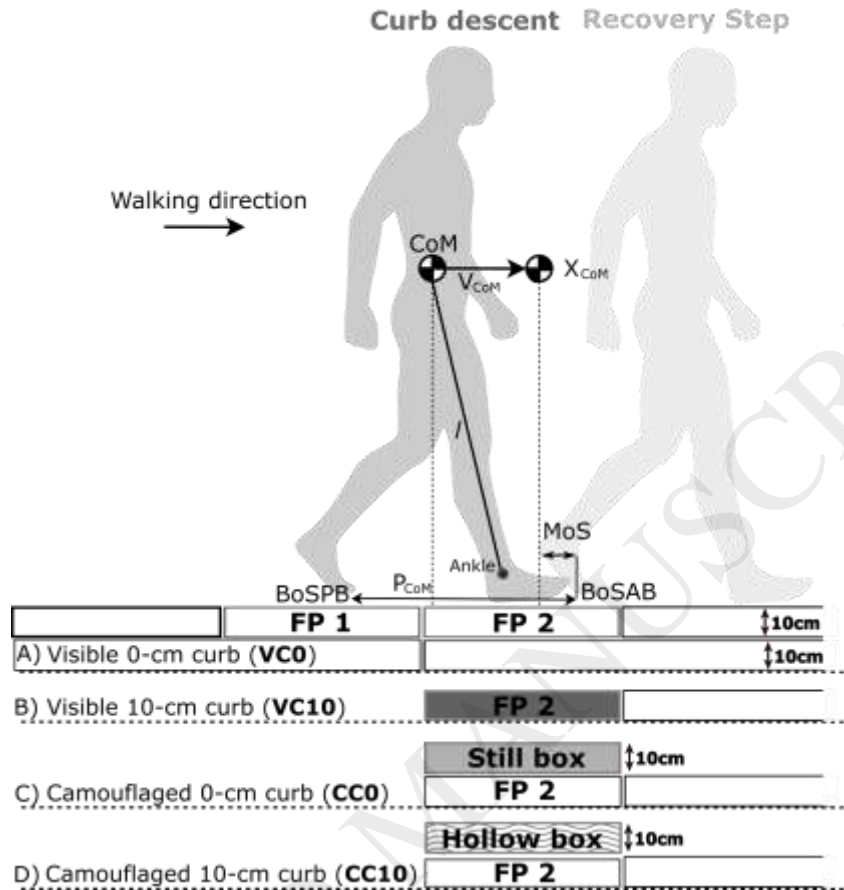
Fig. 1. Schematic illustration of the inverted pendulum model and experimental setup. P_{CoM} represents the horizontal component of the projection of the CoM to the ground, V_{CoM} is the horizontal velocity of the CoM, l is the pendulum length (i.e. the distance between the CoM and the center of the ankle joint in the sagittal plane), BoSAB and BoSPB are the anterior and posterior boundaries of the BoS, respectively, X_{CoM} ($P_{CoM} + \frac{V_{CoM}}{w_0}$) is the extrapolated CoM, where w_0 is the natural frequency of the pendulum used in the model ($\sqrt{g/l}$) with g = 9.81 m/s^2. MoS was determined as the horizontal distance between the BoSAB, defined by the leading toe marker, and the X_{CoM} at foot touchdown in sagittal plane. In the middle of an 8-m walkway, one adjustable forceplate (2nd forceplate; FP 2) was set on four conditions relative to one fixed forceplate (1st forceplate; FP 1): A) visibly flushed with (VC0), B) visibly lowered by 10-cm (visible curb; VC10), C) camouflaged by a wooden, solid box (10-cm height; CC0), and D) camouflaged by a hollow box (10-cm height; CC10). Both solid and hollow forceplate sized boxes were covered by a thin, non-transparent paper.
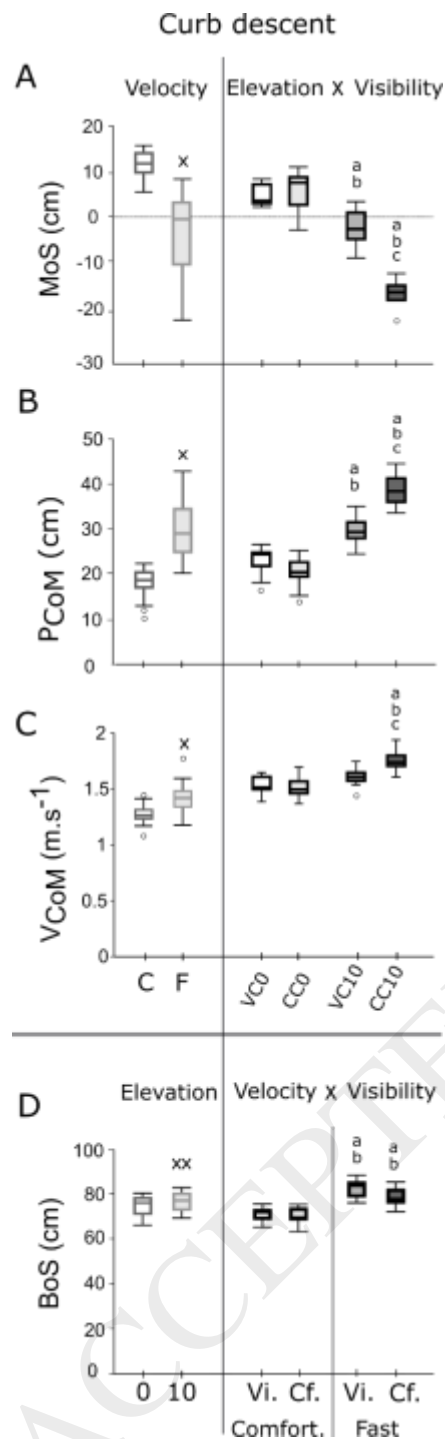
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Fig. 2. Anteroposterior margin of stability analysis at foot touchdown during curb descent (perturbed step). (A) margin of stability (MoS), (B) center-of-mass position (P_{CoM}), (C) center-of-mass velocity (V_{CoM}) and (D) base-of-support (BoS). (A), (B) and (C) represent the main effect of velocity(left) and the *post-hoc* comparisons for elevation × visibility interaction analyses (right). (D) represents the main effect of elevation (left) and *post-hoc* comparisons for a velocity × visibility interaction (right). Error bars denote standard deviation. Significant differences from visible 0-cm curb (VC0), camouflaged curb 0-cm (CC0) and visible -10-cm curb (VC10) are indicated by "a", "b" and "c", respectively. "×" and "××" indicate the between-velocity and between-elevation significant differences, respectively. BoS, X_{CoM} and P_{CoM} were calculated in reference to the posterior boundary of the BoS (toe marker of the trailing limb; BoS_{PB}) at foot touchdown of the leading leg. CC10, -10-cm camouflaged curb. N, normal velocity; F, fast velocity; Vi., visible curb; Cf., camouflaged curb; C, comfortable velocity; F, fast velocity; '°', outlier.
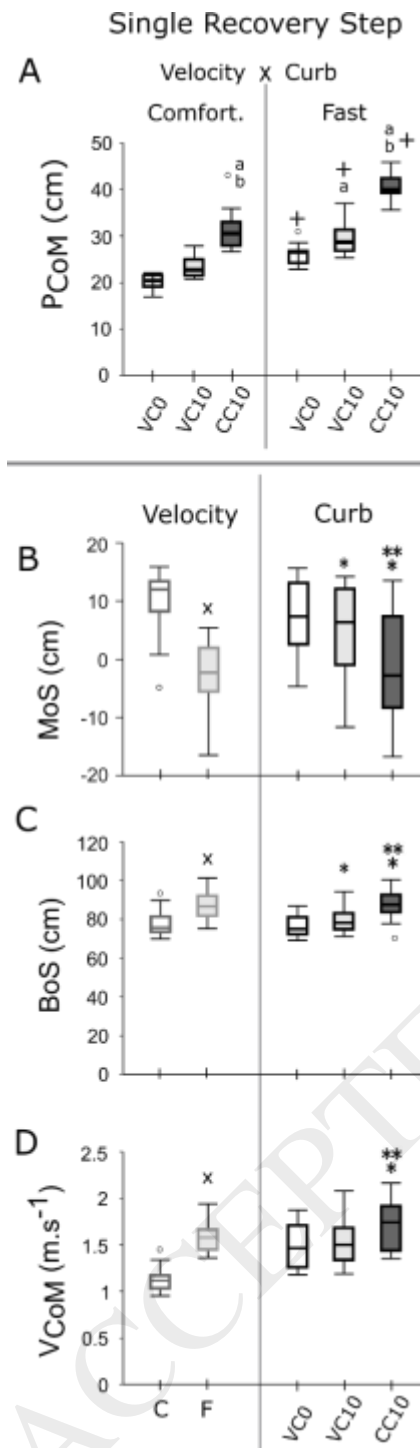
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Fig. 3. Anteroposterior margin of stability analysis at foot touchdown in single-recovery-step. (A) center-of-mass position (P_{CoM}), (B) margin of stability (MoS), (C) base-of-support (BoS) and (D) center-of-mass velocity (V_{CoM}). (A) represents the *post-hoc* comparisons for velocity × curb interaction analysis. Significant differences from visible 0-cm curb (VC0) and visible -10-cm curb (VC10) are indicated by "a", "b", respectively, at both normal and fast walking velocities. A significant between-velocity difference across each curb condition is indicated by "+". (B), (C) and (D) represent main effects of velocity (left) and curb type (right), separated by a solid line. Significant differences from visible 0-cm curb (VC0) and visible -10-cm curb (VC10) are indicated by "*", "**", respectively. "×" indicates the between-velocity significant difference. Error bars denote standard deviation. BoS, X_{CoM} and P_{CoM} were calculated in reference to the posterior boundary of the BoS (toe marker of the trailing limb; BoS_{PB}) at foot touchdown of the leading leg. CC10, -10-cm camouflaged curb. C, comfortable velocity; F, fast velocity; '°', outlier.