***Motor Control,* (Ahead of Print)**
https://doi.org/10.1123/mc.2022-0045

Human Kinetics
ARTICLE

Between a Walk and a Hard Place: How Stepping Patterns Change While Navigating Environmental Obstacles

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Maintaining a consistent relationship between each footfall and the body's motion is a key mechanism to maintain balance while walking. However, environmental features, for example, puddles/obstacles, impose additional constraints on foot placement. This study investigated how healthy young individuals alter foot placements to simultaneously manage body-centric and environmental constraints during an obstacle-crossing task. Consistent step length promotes balance for all steps, whereas accurate foot placement around the obstacle is essential to avoid a trip. While crossing an obstacle, any error in positioning one foot relative to the obstacle can be compensated by selecting the placement of the subsequent step. However, compensation will necessarily alter step length from its average value. The interstep covariance index computed from two consecutive foot placements was used to quantify this tradeoff between body-centric and environmental constraints for six consecutive steps while approaching, crossing, and resuming unobstructed gait after crossing the obstacle. The index declined only when either one or both feet were adjacent to the obstacle. The decline was driven in part by a tendency toward higher step length variability. Thus, changes in the stepping patterns to address the environmental constraint occurred at the cost of the body-centric constraint. However, the step length never ceased to be controlled; the interstep covariance index was positive for all steps. Overall, participants adapted foot placement control to account for the larger threat to balance. The environmental constraint was prioritized only when a potential trip posed greater threat to balance compared with the threat posed by variable step length.

***Keywords*:** adaptive gait, obstacle crossing, foot placement, covariance analysis

While walking on a clear walkway, the foot placement strategy, succinctly expressed as stepping in the direction of an impending fall (Wang & Srinivasan, 2014), is a key mechanism for maintaining balance (Reimann, Fettrow, & Jeka,

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2018; Reimann, Fettrow, Thompson, et al., 2018; Winter, 1995). Modeling work suggested that modulating the placement of the foot is sufficient for maintaining balance while ensuring forward progression (Hof, 2008; Townsend, 1985), and empirical data bore out this view. Systematic changes in foot placement in both the medial–lateral and the anterior–posterior (AP) directions in response to external perturbations indicated that humans control foot placement to maintain balance while walking (Donelan et al., 2004; Joshi & Srinivasan, 2018; O'Connor & Kuo, 2009; Voloshina et al., 2013; Wang & Srinivasan, 2014).

During community ambulation, however, people proactively adapt their stepping patterns to navigate obstacles, puddles, and so on. Adaptations in foot placements can take the form of avoidance (e.g., not stepping into a puddle) or targeting (e.g., stepping onto a stair). Therefore, in such situations, the foot placement must simultaneously account for variations in the body's motion and environment features (locations of various hazards relative to the body); that is, foot placement is simultaneously influenced by a body-centric constraint and an environmental constraint. Appropriately navigating environmental hazards is critical as 17%–59% of falls result from tripping (Berg et al., 1997; Blake et al., 1988; Heijnen & Rietdyk, 2016), and tripping can result from inappropriate foot placement (Chen et al., 1991; Chou & Draganich, 1998; Heijnen et al., 2012; Muir et al., 2020; Patla & Greig, 2006). Therefore, our goal was to study how foot placement is modulated during an obstacle-crossing task to simultaneously accommodate variations in body motion and environmental hazards.

We focused on the foot placements in the AP direction and, in particular, on the stabilization of step length. The body-centric constraint on foot placement is the same for obstructed and unobstructed gait: Foot placement must provide a base of support (BOS) such that the BOS maintains a consistent relation with the center of mass (COM) state (Bosse et al., 2012; Hak et al., 2019; Hof, 2008; Kulkarni et al., 2022; Ohtsu et al., 2019). In the AP direction, this translates into the control of step length; in the absence of any large perturbations, the step length should be relatively consistent. Indeed, during unobstructed walking, changes in step length over one or two steps are typically small (coefficient of variation about 1.5% of the preferred step length; Collins & Kuo, 2013). The environmental constraints, on the other hand, that arise during obstacle crossing take the form of targeting: The feet must be placed appropriately before and after the obstacle to minimize the likelihood of tripping (Chen et al., 1991; Chou & Draganich, 1998; Heijnen et al., 2012; Lowrey et al., 2007).

Humans make small adjustments to foot placement for several consecutive steps while approaching obstacles; foot placements close to the obstacle are more precise compared with those further from the obstacle (Lee et al., 1982; Muir et al., 2019). However, error in foot placement is inevitable due to the noise in the sensorimotor systems. Given the error in one foot placement relative to the obstacle, we want to characterize the adjustment in the subsequent foot placement. Note that maintaining the step length will perpetuate the error from the previous step. In contrast, correcting the error in foot placement will disturb the step length. Thus, a person must choose which constraint to satisfy, and this choice has implications for balance. For example, if the foot is placed too far back behind the obstacle (fp_{-2} in Figure 1b), then the next foot (fp_{-1}) could be placed such that it either (a) preserves step length but is too far back from the obstacle or (b) meets the

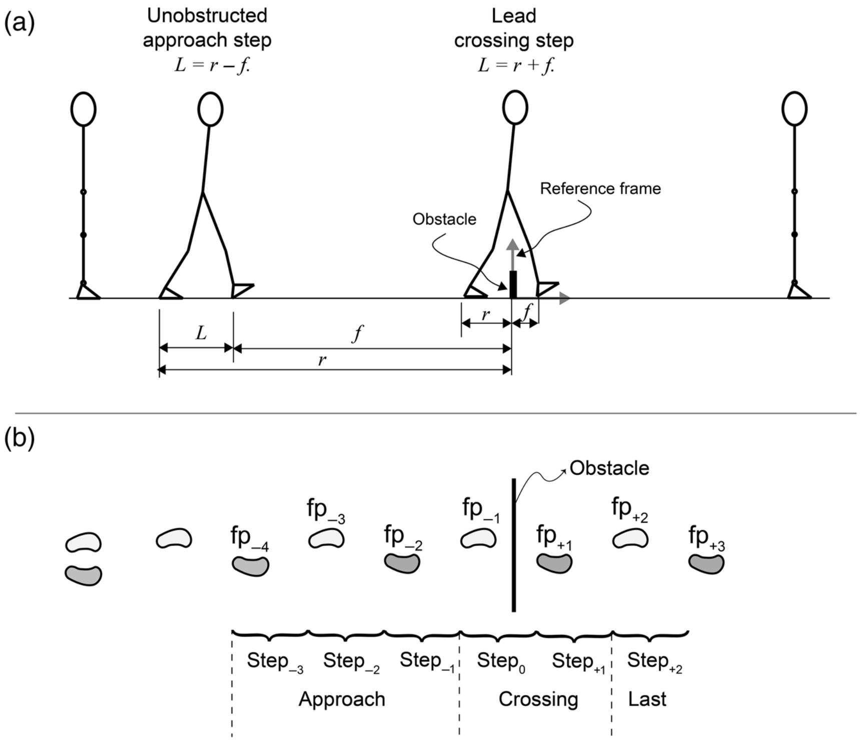

Figure 1 — (a) Illustration of the obstacle-crossing task. Input and output variables for the uncontrolled manifold analysis for one unobstructed and one obstacle-crossing step are defined. (b) The fps while approaching (fp_{-4} to fp_{-1}), crossing (fp_{+1} and fp_{+2}), and after crossing (fp_{+3}) the obstacle. Definitions of steps while approaching ($Step_{-3}$ to $Step_{-1}$), crossing ($Step_0$ and $Step_{+1}$), and after crossing ($Step_{+2}$) the obstacle. fp = foot placement.

optimal foot placement location relative to the obstacle but increases step length. A preserved step length increases the risk of obstacle contact during late swing as the lead foot descends to land beyond the obstacle. However, a longer step will minimize the likelihood of obstacle contact, but it may threaten balance by disturbing the COM–BOS relation.

The control choices will manifest in the covariance structure of the positions of pairs of consecutive foot falls. We previously studied this phenomenon for the obstacle-crossing step by comparing the interstep covariation (ISC) index across age groups (Kulkarni et al., 2021). (The ISC index was called “step-length ISC index” in our previous work. We are renaming this index for reasons explained in the “Methods” section of this paper.) This index quantified the covariation in the distances of the back and the front heels from the obstacle that maintains or stabilizes the step length. Lower values for this index indicated lower step-length stability and, therefore, a prioritization of the environmental constraint (associated with not tripping) over the body-centric constraint (maintaining COM–BOS relation). Older adults demonstrated lower index values compared with young individuals, likely because a perturbation resulting from foot–obstacle contact would be much larger than that resulting from small deviations in the COM–BOS relation and because age-related declines in muscle strength and coordination (Clark & Manini, 2008; Seidler et al., 2010) make recovery from a trip more difficult for older adults.

In contrast to the previous work, our focus here was to identify whether the ISC index changes systematically across multiple consecutive steps during an obstacle-crossing task. Changes in the ISC index across consecutive steps would provide more direct evidence for the tradeoff between the body-centric and environmental constraints. We computed the ISC index for six consecutive steps as healthy young participants approached an obstacle, crossed the obstacle, and then resumed unobstructed gait. We hypothesized that the index would vary across steps. It is known that the variability in the foot position progressively reduces and then increases while approaching and after crossing an obstacle, respectively (Muir et al., 2019), likely reflecting the importance of appropriate foot placement during those phases of the task. Therefore, we predicted that the ISC index would decline during approach and crossing, and it would increase after crossing the obstacle. We also hypothesized that the ISC index would be positive, indicating that the step length is stabilized for all steps. This prediction follows from our earlier work wherein we observed a positive ISC index for the crossing step, when this index is expected to be at its minimum value (Kulkarni et al., 2021).

Methods

Participants

Twenty-six healthy young adults participated in the study. We excluded six participants due to poor kinematic tracking. Therefore, we report data from 20 participants (14 women, 22.3 ± 3.7 years, 1.7 ± 0.1 m, 66.9 ± 14.6 kg). None of the participants reported any orthopedic or neuromuscular disorders. Vision was normal or corrected to normal. The study was approved by the Institutional Review Board of Purdue University, and all participants provided written informed consent.

Equipment and Procedures

Leg dominance was assessed using the Waterloo Footedness Questionnaire—Revised (Elias et al., 1998). Participants walked at their self-selected speed on a 6-m walkway and stepped over an obstacle (Figure 1a). The obstacle was 100 cm wide × 0.4 cm deep. The height of the obstacle was scaled to 25% of the participant's leg length. The obstacle was made of black Masonite and designed to tip if contacted. The starting position was determined for each participant such that they took five steps before reaching the obstacle, crossed the obstacle with the right leg first, and stopped two to three steps later (Figure 1b).

Participants performed 20 trials of walking with an obstacle. We collected kinematic data at 100 Hz with a motion capture system (Vicon Vero) with marker clusters placed bilaterally on the lower back, thigh, shank, and foot. We digitized the joint centers and the heels to identify their locations relative to the marker clusters. However, only the heel positions are utilized in the present work. We also digitized the top edge of the obstacle to identify its position.

Data Analysis

Some trials were discarded due to poor kinematic tracking. To have the same number of trials for all participants, we selected 15 trials with good kinematic data. Fifteen trials were sufficient for reliable quantification of the ISC index, which was obtained from the computations of the uncontrolled manifold method as described later (Rosenblatt & Hurt, 2019). We filtered all kinematic data using a zero-lag, fourth-order, low-pass Butterworth filter with a cutoff of 7 Hz. We identified seven foot placements (fp; Figure 1b) using the AP position data of the digitized heel positions (Desailly et al., 2009). The absolute distances of the rear and the front heel from the obstacle, r and f, respectively, at heel contact were computed and normalized by participant's height (Figure 1a). Consequently, the normalized distances are expressed as "statures," and all variances are expressed as "stature^2" in the "Results" section.

To compute the covariation between pairs of consecutive foot placements, we adopted a geometrical analysis that resembled closely the uncontrolled manifold (UCM) method (Scholz & Schoner, 1999) as well as the goal equivalent manifold method (Cusumano & Dingwell, 2013). The computations of the UCM method were well suited to address our research questions, and therefore, we adopted the computations and outcome measures provided by the UCM method. However, we used different terminology from that typically associated with either the UCM or the goal equivalent manifold methods because of a key difference in our problem formulation. Within the UCM and goal equivalent manifold methods, the input variables were typically body variables (e.g., joint angles or muscle activations). In contrast, our input variables were absolute distances of the feet from an environmental landmark. Therefore, the good and bad variance components and the ISC index obtained from the UCM analysis were called goal-equivalent variance (GEV), non-goal-equivalent variance (NGEV), and the ISC index, respectively, in this work.

We first assumed that the goal of each foot placement was to achieve a prescribed step length. Hence, the step length was considered as the output variable. The prescribed step length was not known a priori; the across-trial average step length for a given step was assumed to be the prescribed value for that step. Given that this analysis was being performed while considering the location of the feet relative to the obstacle, we assumed that the output step length was determined by the distance of two consecutive foot placements, f and r, relative to the obstacle. We then evaluated the hypothesis that the input variables, that is, the normalized absolute heel distances, f and r, covaried to minimize the variance of the output variable, that is, to stabilize the normalized step length (L; Figure 1a).

We performed the covariation analysis separately for the six steps. The constraint relating the heel distances to the step length was: $r - f = L$ for all steps during approach, $r + f = L$ when the first leg crossed the obstacle, and $f - r = L$ for the last two steps (Figure 1a). The partial derivatives of the constraint(s) yielded the Jacobian: $J = [\pm 1 \ \ \pm 1]$, where appropriate entries in the Jacobian (either +1 or −1) were selected according to the step being analyzed. The one-dimensional null space of J defined the solution space; any pair of (f, r) values that lies on this space yields the same step length. Across-trial changes in the consecutive heel distances for a given step that aligned with the solution space did not change the step length (hence called “goal-equivalent”). Conversely, changes in the same pair of heel distances orthogonal to the solution space changed step length (hence called “non-goal-equivalent”). The deviations in r and f for each trial from their across-trial means were projected onto the solution space and the space orthogonal to the solution space. The variances in these projections were the GEV and the NGEV, respectively. The ISC index was then calculated as:

$$\mathrm{ISC} = \frac{\mathrm{GEV} - \mathrm{NGEV}}{\left(\frac{\mathrm{GEV} + \mathrm{NGEV}}{2}\right)}.$$

The ISC index, ranging from −2 to 2, was z-transformed for statistical analysis:

$$\mathrm{ISC}_Z = \frac{1}{2} \times \log\left[\frac{2 + \mathrm{ISC}}{2 - \mathrm{ISC}}\right],$$

$\mathrm{ISC} = 0$ translated to $\mathrm{ISC}_Z = 0$. Therefore, $\mathrm{ISC}_Z > 0$ indicated GEV > NGEV which, in turn, implied that r and f covaried to stabilize the step length; $\mathrm{ISC}_Z < 0$ indicated that r and f covaried to destabilize the step length, and $\mathrm{ISC}_Z = 0$ indicated that there was no task-specific covariation in r and f.

Statistics

To determine whether covariation in r and f stabilized the step length, we performed separate, one-sample t tests to identify whether ISC_Z was significantly different from zero for each step. To determine whether the step affected the dependent variables, we performed one-way analyses of variance with step as a repeated measure. The dependent variables were: ISC_Z, GEV and NGEV, step length, foot placement variance, and step length variance. For all analyses of variance, we fit a generalized linear model using the GLIMMIX procedure. For step length, participant was the random effect, and trial number was the random effect nested within each participant. For all other dependent variables, participant was the random effect. Tukey–Kramer adjustments were used to perform all pairwise comparisons when a main effect was detected. Analyses were performed in SAS (version 9.4) with significance level 0.05.

Results

All participants were right-leg dominant as measured by the Waterloo Footedness Questionnaire. The Waterloo Footedness Questionnaire scores were 8.25 ± 4.26 (across-participant mean ± *SD*).

The ISC_Z index was significantly greater than zero for all steps, $t(19) \le 18.56$, $p < .0001$, Cohen’s $d \ge 1.43$ (Figure 2a).

There was a significant effect of step on the ISC_Z index, $F(5, 95) = 30.60$, $p < .0001$, $\eta_p^2 = .61$ (Figure 2a). The index was lower for the steps with either one or both feet adjacent to the obstacle (i.e., step_{-1}, step_0, step_{+1}) compared with steps that were farther from the obstacle (i.e., step_{-3}, step_{-2}, and step_{+2}).

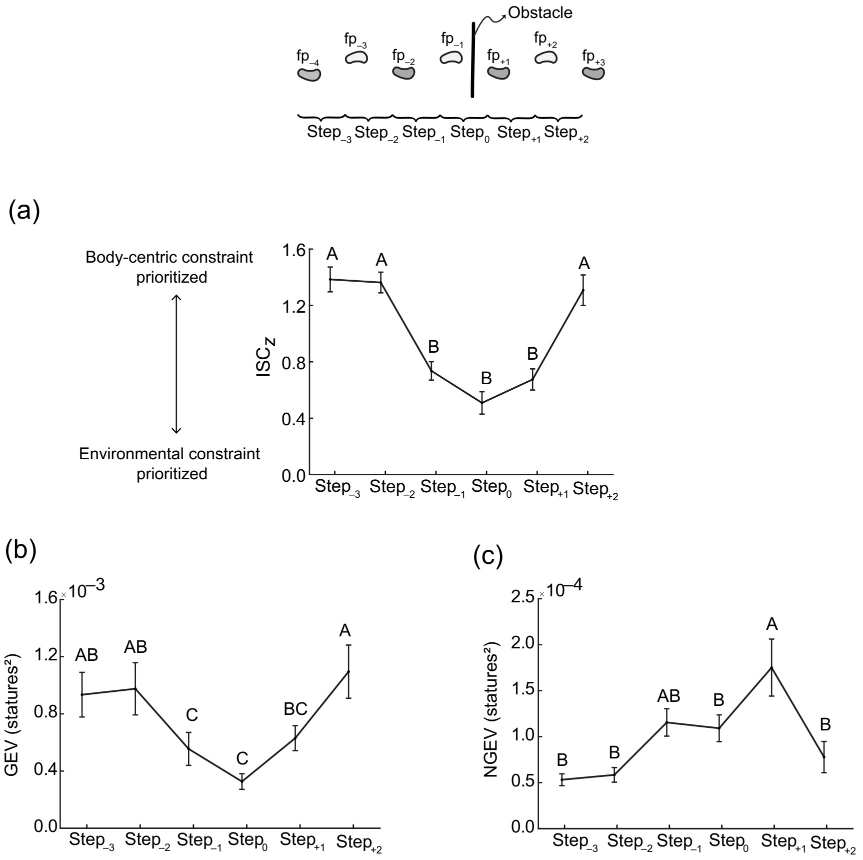

Figure 2 — Mean ± *SE* of the ISC index (a), GEV (b), and NGEV (c). Heel distances normalized by participant height are expressed in "statures." These normalized distances were used to compute the variances. Steps that do not have letters in common are significantly different from each other (i.e., A is different from B, but A is not different from AB). ISC = interstep covariation; GEV = goal-equivalent variance; NGEV = non-goal-equivalent variance.

There was a significant effect of step on GEV, $F(5, 95) = 10.58$, $p < .0001$, $\eta_p^2 = .36$ (Figure 2b). GEV was lower for the lead crossing step (i.e., when the first [right] leg crossed the obstacle; step$_0$) compared with all other steps except step$_{-1}$. Furthermore, GEV was lower for step$_{-1}$ compared with the first two steps (step$_{-3}$ and step$_{-2}$), and GEV was higher for step$_{+2}$ compared with step$_{-1}$ and step$_{+1}$.

There was a significant effect of step on NGEV, $F(5, 95) = 8.26$, $p < .0001$, $\eta_p^2 = .30$ (Figure 2c). NGEV was higher for the trail crossing step (i.e., when the second [left] leg crossed the obstacle; step$_{+1}$) compared with all steps except step$_{-1}$.

There was a significant effect of step on the step length, $F(5, 1775) = 266.48$, $p < .0001$, $\eta_p^2 = .55$ (Figure 3a). The lead crossing step (step$_0$) was longer than all other steps. The trail crossing step (step$_{+1}$) was longer than all other steps

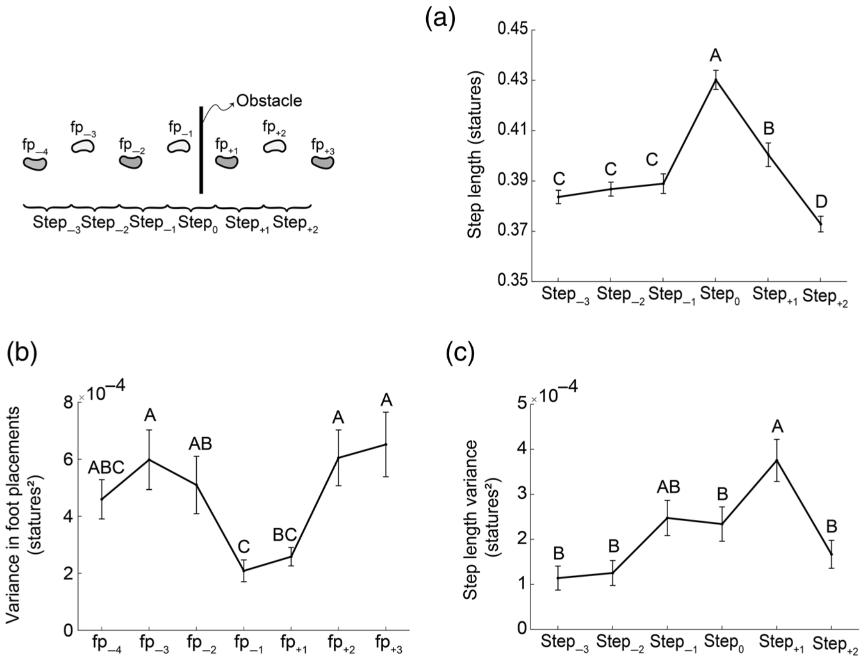

Figure 3 — Mean ± *SE* of the step length (a), variance in fp (b), and variance in step length (c). The fps are distances of the corresponding heel from the obstacle normalized by participant height and are expressed in "statures." These normalized distances were used to compute the variances. Steps or fps that do not have letters in common are significantly different from each other (i.e., A is different from B, but A is not different from AB). fp = foot placement.

except the lead crossing step (step$_0$). The last step (step$_{+2}$) was shorter than all other steps.

There was a significant effect of step on the variance in heel distances from the obstacle, $F(6, 114) = 8.64; p < .0001, \eta_p^2 = .31$ (Figure 3b). The variance was lower for fp$_{-1}$ compared with all other foot placements except fp$_{-4}$ and fp$_{+1}$. The variance was lower for fp$_{+1}$ compared with all other foot placements except fp$_{-1}$ and fp$_{-4}$.

There was a significant effect of step on the step length variance, $F(5, 95) = 8.26, p < .0001; \eta_p^2 = .30$ (Figure 3c). Step length variance was higher for step$_{+1}$ compared with all other steps except step$_{-1}$.

Discussion

The goal of this work was to identify how stepping patterns are proactively modulated during an obstacle-crossing task to manage body-centric and environmental constraints on foot placement. The body-centric constraint arises from the need to maintain the COM–BOS relation that helps to preserve balance for all steps. The environmental constraint arises from the need to place the feet at appropriate locations relative to the obstacle to avoid a trip. We utilized the ISC index to identify how the two constraints are satisfied and whether one constraint is prioritized over the other for six steps during the obstacle-crossing task. A lower value of the ISC index indicated prioritization of the environmental constraint and vice versa. The data supported our hypotheses. The ISC_Z index declined for the steps when one or both feet were immediately adjacent to the obstacle, and it was higher for the steps farther from the obstacle—both before and after crossing the obstacle. This demonstrates that the stepping patterns changed to prioritize the environmental constraint when it was more salient; this proactive adaptation was likely in response to the larger threat posed by a trip while crossing the obstacle. However, the front and back heel distances relative to the obstacle covaried to stabilize the step length for all steps. This indicates that step length was always controlled, presumably to control COM motion, even when the obstacle imposed additional constraints on foot placement.

The ISC Index Identifies the Prioritization Between Dueling Constraints

In principle, the body-centric and environmental constraints on foot placement during obstacle-crossing tasks can be simultaneously satisfied with ideal foot placement. In fact, the declining foot placement variability during approach, observed previously in athletes during long jump (Lee et al., 1982) and hurdling (Smirniotou et al., 2022) and in healthy young and older individuals during obstacle crossing while walking (Muir et al., 2019), is a strategy to achieve this ideal. However, humans cannot achieve perfectly accurate foot placement due to inherent noise in sensorimotor systems. So, in addition to maximizing stepping accuracy, the covariance between consecutive steps could also be manipulated to reduce the effect of noise on critical task variables.

The analysis that we employed reveals whether such a covariation strategy is used and how the strategy changes across steps. The integrated inspection of the ISC index (although the statistics were performed on the z-transformed ISC_Z metric, we henceforth omit the subscript "z" for convenience) and the variance components GEV and NGEV reveals that the individuals prioritize the environmental constraint at the expense of the body-centric constraint during obstacle crossing. $ISC = 0$ would indicate that there was no covariation between consecutive foot placements. Instead, ISC indices were positive for all the analyzed steps (Figure 2a), indicating that step length was stabilized via covariation between consecutive foot placements. Furthermore, the decline in ISC during approach indicated that the covariation between the foot placements shifted from stabilizing the step length to stabilizing foot placement. These changes were driven by lower GEV (lower covariation to stabilize step length; Figure 2b) and accompanied by the tendency of NGEV to increase, indicating that the body-centric constraint was not satisfied to the same extent as for other steps (Figure 2c). NGEV increased by 100% from $step_{-3}$ to $step_{-1}$, although this difference was not statistically significant due to interindividual differences. Note that it is important to consider changes in the variance components when interpreting changes in the ISC index. For example, if both GEV and NGEV reduced, but GEV reduced more than NGEV, it would also yield a lower ISC index. This behavior would indicate that the individual improved foot placement accuracy without compromising on the step length stabilization; that is, the two constraints were satisfied to some degree (as reflected by the lower magnitude of the variances) but not at the cost of any one of the constraints. The healthy young adults observed here did not demonstrate the strategy or ability to satisfy both constraints concurrently; rather, they prioritized differently based on proximity to the obstacle.

When approaching and crossing an obstacle, the threat to balance varies with the step. Trip risk exists only for the crossing steps, and it poses a significant threat to balance. In contrast, the threat to balance associated with weaker step length stabilization exists for all steps, but this threat is relatively low. The passive dynamics of human gait are stable in the AP direction, suggesting that the gait cycle is robust to some variability in step length (Kuo & Donelan, 2010). Given that the two threats to balance are likely disproportionate, the control system prioritizes management of the greater threat, as revealed in the selective reduction in the ISC index for the steps adjacent to the obstacle.

The positive ISC indices for all steps indicate that step length is controlled for adaptive gait tasks. It is known that the step length is reactively controlled when gait is externally perturbed (Collins & Kuo, 2013; Joshi & Srinivasan, 2018; McAndrew et al., 2010; O'Connor & Kuo, 2009; Voloshina et al., 2013; Wang & Srinivasan, 2014). For unperturbed gait, step length is thought to arise from passive dynamics and local, spinal feedback control (Bauby & Kuo, 2000; O'Connor & Kuo, 2009). Here, we extended these earlier observations—when the walkway contains an obstacle, step length is proactively controlled during the approach and crossing phases, likely using supraspinal vision-based information about the obstacle (see below). The active control is manifested not only as changes in the step length (mean step length is longer for the crossing steps relative to earlier steps; Figure 3a) but also in more subtle ways that reveal shifting control priorities (as for the approach steps; Figures 2a and 3a).

Satisfying the environmental constraint requires visual information about the obstacle's position (Hollands et al., 2017; Patla, 1997). The position of the obstacle relative to the walker must be sampled in a specific region during approach to appropriately place the feet relative to the obstacle (Diaz et al., 2018). Foot-targeting tasks indicate that the visual information is used in both a feedforward and feedback manner (Hollands et al., 2017; Matthis et al., 2015; Reynolds & Day, 2005; Young & Hollands, 2012). Therefore, the adjustment of the ISC index observed in our study (Figure 2a) is likely due to both feedforward and feedback information derived from the visual system.

The Interstep Covariance Index and Gait Stability

We suggest that the ISC index for the crossing steps may be *inversely* related to gait stability. This view is based on the interpretation of this index in the context of small perturbations (arising at every step from neuromuscular noise, say) as well as large perturbations (arising from a trip). We define stable gait as one that does not lead to a fall despite perturbations (Bruijn et al., 2013). If there were multiple perturbations that threatened balance, prioritizing the greater threat would be a reasonable strategy to avoid falls. From this point of view, a lower ISC index for the crossing step (or, perhaps, the net decline in the index over all steps) is a strategy to avoid the large perturbation that could arise from a trip, and therefore, the lower ISC index may be associated with greater gait stability.

Another view would be to argue that a lower ISC index reflects lower step length stability, and lower step length stability (usually inferred from higher step length variability) indicates less stable gait. This interpretation could be supported by the fact that fall risk is positively correlated with step length variability (Maki, 1997). However, associations between the variability of spatiotemporal gait measures and gait stability are identified usually during unobstructed walking. While extending this approach to obstructed gait, any additional constraints imposed by the task and the resulting alterations in control must be considered (Bruijn et al., 2013). For example, individuals who choose to walk with narrower steps (the control strategy) will tend to be less stable independent of the variability in step width (Bruijn et al., 2013). In the present case, the control strategy is to systematically increase AP foot placement accuracy, which is an adaptive response to the constraints imposed by the obstacle. As this adaptation leads to lower ISC indices, it is more likely that the ISC index, at least for the crossing steps, is inversely related to gait stability.

We view these ideas as a testable hypothesis; determining whether fall rates correlate with either the ISC index for the crossing steps or the net decline in the index is an area of future research.

Future Work

The ISC index can be employed to more fully understand how visual information of the environment is used to adapt the rudimentary gait pattern. This, in turn, will help identify the biomechanical and neural mechanisms that underlie the causal relation between visual behavior and impaired lower limb coordination (Hollands et al., 2017). Note, however, that the ISC index cannot be computed for unobstructed walking; although the computations can be performed in an arbitrary laboratory-fixed reference frame, the results will be difficult to interpret. The ISC index could be computed in a reference frame fixed to the body, at the COM, say, during unobstructed walking (Verrel et al., 2012). However, this approach would not address how environmental features affect gait.

Note that our analysis is limited to peripheral mechanical variables. Our observations need to be explained further in terms of body variables (e.g., leg joint kinematics) and, eventually, in terms of neural processes. In this regard, the referent control framework provides a promising approach (Feldman et al., 2021). According to this theory, locomotion arises when neurons receiving multidimensional sensory inputs detect a deflection of the current body configuration from a referent body configuration—a desired configuration wherein all muscles would be at the threshold of activation—and generate activity depending on this deflection. This view, which provides a high-level description of the process of action generation, is complemented with a hierarchy of mappings between task-level descriptions (e.g., the global referent configuration) and low-level muscles and motor units (the referent variable at the muscle level would be the threshold of the tonic stretch reflex λ; Latash, 2021). Our analysis of foot positions describes one level of this hypothetical hierarchy. Specification of the body referent configuration would lead to the specification of foot trajectories, perhaps influenced by visual information regarding the obstacle, and the covariance patterns that we describe emerge from the interaction between the referent foot trajectories and the local feedback processes.

Finally, as only the positions of the heels and the obstacle are required to obtain our ISC index, the index is not affected by errors in joint angle estimation from kinematic marker data that would influence outcome measures based on joint kinematics (e.g., Krishnan et al., 2013). Furthermore, different measurement systems could be employed to obtain the data (e.g., pressure-sensitive mats), making this index convenient for clinical use. We have demonstrated a large decrement in this index for the crossing step in healthy older compared with younger individuals (Kulkarni et al., 2021) and in persons with Parkinson disease compared with age-matched controls (Ambike et al., 2021). Although we suggested earlier that these declines were deficits arising from age- or pathology-related neurophysiological changes, we plan to investigate whether these changes are, indeed, deficits or adaptations, as suggested in this work. The index could also be useful in studying the gait of persons with Parkinson's disease in response to visual cues on the floor (visual stimuli are often used to improve walking), and during freezing of gait episodes that can occur while such persons approach narrow doorways (Almeida & Lebold, 2010; Azulay et al., 2006).

Conclusion

Covariance analysis demonstrated that healthy young adults prioritize between conflicting constraints on foot placement during obstacle crossing. Decline in the interstep covariance index while approaching and crossing an obstacle, along with concomitant changes in the variance components (GEV and NGEV), indicated that the environmental constraint (accurate foot placement) was prioritized at the cost of the body-centric constraint to maintain step length. The environmental constraint was prioritized only when a potential trip posed a greater threat to balance compared with the threat posed by variation in the COM–BOS relation arising from variable step length. Therefore, foot placement control adapted to account for the larger threat to balance.

Acknowledgments

This work was supported by the Bilsland Dissertation Fellowship awarded by the Office of Interdisciplinary Graduate Programs and the Corrigan Professional Development Grant awarded by the Department of Health and Kinesiology at Purdue University.

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