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Visual Regulation of Gait: Zeroing in on a Solution to the Complex Terrain Problem

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We examine the theoretical understanding of visual gait regulation that has emerged from decades of research since the publication of Lee, Lishman, and Thompson's (1982) classic study of elite long jumpers. The first round of research identified specific informational variables, parameters of the action system, and laws of control that capture the coupling of perception and action in this context, but left unanswered important questions about why visual information is sampled in an intermittent manner and how the strategies that actors adopt ensure stability and energetic efficiency. More recent developments lead to a refined view according to which visual information is used at a specific phase of the gait cycle to modify the parameters that govern the passive dynamics of the body. We then present the results of a new experiment designed to test the prediction that when the terrain offers multiple foothold options for a given step, walkers' choices will be constrained by a strong preference for not interfering with the natural, ballistic movement of the body throughout the single support phase of that step. The findings are consistent with this prediction and support a view of visual gait regulation that is concordant with contemporary accounts of how actors use both active and passive modes of control.

Public Significance Statement
Walking over complex terrain such as a rocky trail or a crumbling sidewalk demands that movements of the body be precise, coordinated, and efficient. Although vision plays an integral role in adapting the ongoing gait cycle to the environment, walkers do not need to continually look at the upcoming terrain. Even a brief glance at the next foot target is sufficient for accurate stepping, as long as that glance occurs at just the right time. In this study, we provide evidence that brief glances are sufficient because walkers prefer to make gait adjustments at discrete intervals of each step and allow the body to move under its own momentum and the influence of gravity for the rest of the step. This could be how walkers attempt to maintain energetic efficiency while walking over complex terrain.

Keywords: locomotion, visual control, perception-action coupling, dynamic walking, complex terrain

In 1982, Lee, Lishman, and Thomson published a seminal article on the visual regulation of gait. Although the study focused on the movements of elite long jumpers as they approached the takeoff board, the authors' motivation was much broader—to understand how humans regulate gait in cluttered environments to avoid obstacles, identify safe target footholds, and ensure that the feet land on those footholds. Even putting aside the findings and conclusions of Lee et al., the topic of investigation itself makes the study noteworthy. Before the early 1980s, the question of how gait is regulated to accommodate variations in terrain had taken a back seat to investigations of the biomechanical and neurophysiological bases of walking and running over flat, obstacle-free terrain. Lee et al. brought into the spotlight what has come to be known as the *rough terrain* (or *complex terrain*) problem (Warren, 2007).[1]

The investigation of locomotion over complex terrain forces one to take seriously the role of perceptual information in general and visual information in particular. Over the past 35 years, much has been learned about the coupling of perception and action during walking and running over irregular surfaces. There is now an abundance of empirical findings about how people use visual

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[1] We prefer the term *complex terrain* because surfaces do not have to be rough to present challenges for bipedal locomotion (e.g., patches of ice, puddles, and potholes).

information to step over obstacles and ensure placement of the feet on safe target footholds. Our first aim in this article is to examine the theoretical understanding of what it means for gait to be visually regulated that has emerged from this research. To our knowledge, this is the first attempt to situate the large body of research on visual gait regulation, which spans more than three decades, into a cohesive theoretical framework. In keeping with the theme of this special issue, we attempt to highlight the links between the classic works on this topic and contemporary research. To that end, we then discuss recent developments in the biomechanics of walking that may further advance our theoretical understanding, particularly as it pertains to the question of why visual information about the upcoming terrain is primarily used during a particular phase of the gait cycle. We propose that the way in which walkers intermittently sample visual information is rooted in a preference to exploit one's biomechanical structure by moving ballistically during the single support phase of each step; that is, by not interfering with the passive trajectory of the center of mass (COM) once the step is underway. Lastly, we report the results of a new experiment designed to test predictions derived from this hypothesis about where walkers choose to step when more than one option exists.

Visual Regulation of Gait in Long Jumping

Before the publication of Lee et al. (1982) the conventional wisdom among coaches was that the long-jumper's skill lies in the ability to consistently reproduce a well-practiced movement (Teel, 1981). Lee et al. revealed that, in fact, proper foot placement on the takeoff board is ensured by using visual information to precisely modulate specific gait parameters toward the end of the run-up—that is, by coupling perception and action. The crucial evidence was the observation that the *SE* in stride length, which is impressively small (~3 cm) for most of the approach, sharply increases during the last few strides. At the same time, the *SE* in footfall position, which gradually increases for most of the approach, sharply decreases.

Lee et al. (1982) attributed these findings to a switch in strategy "from trying to produce a stereotyped stride pattern to regulating their strides in terms of the visually perceived relationship to the board, in order to hit it" (p. 452). Montagne, Glize, Cornus, Quaine, and Laurent (2000) then took this conclusion a step farther by showing that the entire approach (including the initial phase that had been deemed stereotyped) could be regulated by a "funnel-like" control mechanism (Bootsma, Houbiers, Whiting, & van Wieringen, 1991) in which adjustments are not made until later in the approach simply because the necessary adjustments are too small to be detected. This is appealing because it eliminates the need to posit two distinct strategies and a mechanism to switch from one to the other.

The ascending-descending pattern of variability observed by Lee et al. (1982) has been replicated by others and found across a range of skill levels including elite long jumpers (Hay, 1988), high-school level jumpers (Berg, Wade, & Greer, 1994), and novices with no long-jumping experience whatsoever (Scott, Li, & Davids, 1997) as well as at walking speed (Moraes, Lewis, & Patla, 2004) and when stepping over an obstacle (Patla & Greig, 2006). These findings reinforce the notion that the coupling of visual information and gait is not a skill that emerges only after specialized training or when the task demands an extremely high degree of precision. The specific optical variables or action variables involved in this coupling may change over time with practice, leading to improvements in performance. Likewise, the variables that are coupled during long jumping may differ from those that are coupled during obstacle crossing. Nevertheless, the ability to couple visual information and gait is a general solution to the problem of controlling locomotion in complex terrain insofar as it is characteristic of performance at all skill levels and across different contexts.

A second significant contribution of Lee et al. (1982) was the introduction of a visual control strategy (or control law) that formally captures the mapping from information to action. Although Gibson (1958) had laid the groundwork by proposing "formulae" for the visual guidance of locomotion, these formulae were qualitative. The strategy proposed by Lee et al. describes how the modulation of a specific action variable (vertical impulse) by a specific optical variable (τ) ensures that the foot strikes the takeoff board. They first established that stride length is adjusted during the zeroing-in phase by regulating flight time (a temporal parameter) rather than thrust length or landing length (spatial parameters). It followed that the relevant information may be that which specifies how far the athlete is from the take-off board in time rather than in space. In this way, Lee et al. reframed a problem that demands spatial precision in terms of spatiotemporal coordination. They proposed that long jumpers rely on information about time-to-contact with the take-off board, which is specified by the optical variable τ, and regulate flight time via vertical thrust to fill the remaining time available for flight, which is the time-to-contact minus the support times. Specifically, they proposed that the mean change in impulse in relation to current impulse is specified by the ratio of the optically specified required average flight time to the optically specified current flight time. The details of this account were refined in follow-up studies. On the perception side, de Rugy, Montagne, and colleagues (De Rugy, Montagne, Buekers, & Laurent, 2000a, 2000b, 2001; see also, Berg & Mark, 2005) demonstrated that the perceptual system is more flexible and able to use other variants of τ to regulate stride length. On the action side, the claim that actors regulate vertical impulse alone was debated in an exchange between Warren (Warren & Yaffe, 1989; Warren, Young, & Lee, 1986) and Patla (Patla, 1989; Patla, Robinson, Samways, & Armstrong, 1989).

Taken together, Lee et al. (1982) and the studies of long jumping and related tasks that followed brought to the forefront questions about how visual information is used to regulate gait during locomotion over complex terrain. It is clear from this body of research that gait is tightly regulated by visual information during the final phase of the run-up to the take-off board and arguably, during the preceding approach phase as well (Montagne et al., 2000). It is also clear that such regulation, and not simply the ability to reproduce a highly practice pattern of stepping, plays a critical role in satisfying the demands for spatial and temporal precision.

The Perception-Action Coupling Account

What is less clear is how we should think about this form of control. What exactly does it mean for gait to be visually regulated? Montagne et al. (2000) invoked the notion of *perception-*

action coupling (Warren, 1988) to characterize the regulation of gait based on vision. By this account, the control of action is fundamentally "information-based" rather than reliant on an internal model of the environment (Warren, 1988, 1998, 2006; Zhao & Warren, 2015). The relevant information is carried in higher-order relations among elementary variables of energy (e.g., optical, acoustic, and mechanical) arrays, which specify properties of the actor's relation to its environment that are relevant to the particular task (Bootsma et al., 1997).[2]

On the other side of the perception-action coupling, the formation of synergies constrains the high-dimensional action system, such that it behaves as a system with a small number of degrees of freedom. The remaining free variables of the action system are modulated by some informational variable in a task-specific manner, according to some law of control (Warren, 1988), such that changes in the available information effect changes in behavior that move the actor closer to its goal state. In this sense, the realized behavior is emergent rather than planned in advance (Warren, 2006).

The focus of this account is actions that are controlled by information that is currently available (i.e., "on-line control"). Tasks that involve off-line control, such as navigating through a cluttered room after the lights are turned off or steering toward a target that temporarily goes out of view, have traditionally fell outside the scope of the information-based account and arguably lend themselves to an explanation in terms of "model-based control" (Loomis & Beall, 1998, 2004; but see Zhao & Warren, 2015 for an attempt to expand the scope of information-based control).

The Perception-Action Coupling Account of Walking Over Complex Terrain

de Rugy, Taga, Montagne, Buekers, and Laurent (2002) put these ideas to work in developing a detailed model of the visual control of foot placement during walking. In their model, steady-state locomotion emerges from the global entrainment of oscillatory activity from a neural rhythm generator and rhythmic movements of the musculoskeletal system. Changes in step length result from modulation of ankle extensors during push-off and hip flexors during both push-off and the beginning of the swing phase. These serve as the free variables of the action system that are modulated by information. Specifically, the perceptual and motor systems are linked such that the strength of modulation is determined by visual information about the required change in step period. Thus, if the visual information specifies a difference between the current step period and the step period needed to land on a target, the activity of the ankle extensors and hip flexors is modulated, which in turn alters step length to ensure that the foot lands on the target. Depending on the circumstances, the changes in step length needed to erase the "error" in step length may take place in a single step or may be spread out over several steps. Model simulations reveal the same relationship between the step number at which regulations are first observed and the size of the required adjustment that was interpreted by Montagne et al. (2000) as evidence of perception-action coupling, as well as the trademark decrease in foot placement variability reported by Lee et al. (1982) and others.

Open Questions About the Coupling of Perception and Action

The de Rugy model serves as an existence proof that certain aspects of visual gait regulation, as well as some pertinent empirical findings, can be captured by directly coupling information in optic flow to specific parameters of the action system. The model is also useful in making explicit certain important assumptions that underlie the perception-action coupling account of the visual control of gait. The authors clearly identified the specific variables on both the information side and the action side, as well as the mapping between the two. To their credit, this is one of the most detailed models of perception-action coupling that exists in the literature.

Nevertheless, the de Rugy model was built on an understanding of perception-action coupling that was state-of-the-art in the late 1990s and early 2000s. Significant theoretical developments have taken place over the past 15 years, and these developments lead to exciting new insights into the visual regulation of gait. To help the reader appreciate the motivation for these developments, let us consider two important questions about visual gait regulation that have eluded explanation until recently.

Question #1: Why is Visual Information About the Upcoming Terrain Sampled Intermittently and During a Particular Phase of the Gait Cycle?

No account of any visually guided action would be complete without an understanding of whether visual control and visual sampling are continuous or intermittent, and why. The first part of the question is an empirical issue and, for the task of guiding foot placement to ensure landing on safe target footholds, the evidence is unequivocal—visual information is sampled and used in an intermittent rather than a continuous manner. That is, walkers rely primarily on visual information that is sampled during discrete intervals that occur during a specific phase of the gait cycle rather than continuously throughout the entire gait cycle.

Let us begin with evidence that the swinging foot is not continuously guided to the upcoming target. Rather, visual information about the location of a potential foothold for a given step is primarily used before the step to that foothold has been initiated. Once the foot leaves the ground, visual information about the upcoming target is not needed. We recently demonstrated this by instructing subjects to walk along a short path while attempting to step on a series of small targets arranged like stepping stones (Matthis, Barton, & Fajen, 2015). The targets were circular patches of light projected onto the floor by an LCD projector and subjects' movements were tracked by a motion capture system. The projection system and the motion capture system were synchronized, which allowed us to manipulate the visibility of individual targets at specific points in the gait cycle. The entire array of targets was

[2] In many information-based models, the property of the actor-environment system that is specified is the sufficiency of the actor's current state (Fajen, 2005). For example, τ-dot specifies the sufficiency of the actor's current deceleration for braking to avoid a collision (Lee, 1976; Yilmaz & Warren, 1995); the tangent of the optical acceleration of the elevation angle of a baseball specifies the sufficiency of the outfielder's current running speed for arriving at the landing location on time to catch the ball (Chapman, 1968).

visible to subjects at the beginning of each trial, but each individual target disappeared at some point before the subject's foot landed on that target. The main finding was that when each target was extinguished after toe-off of the step to that target, stepping accuracy and precision were largely unaffected. Extinguishing targets during the previous step had a much stronger affect. Thus, although people are capable of using visual information during the swing phase to improve stepping accuracy when taking a single step (Reynolds & Day, 2005b), visual information is primarily used before step initiation during continuous walking over complex terrain.

If visual information is not used in a continuous manner to guide the limbs throughout the entire gait cycle, then there may be a particular phase of the gait cycle that is prioritized for visual control. If so, intermittent sampling of the visual field should be sufficient to allow walkers to successfully negotiate complex terrain, provided that sampling occurs at the right time. Laurent and Thomson (1988) tested this prediction almost 30 years ago. Subjects were instructed to approach and step on a small target at the far end of a walkway, similar to the task of approaching and stepping on a take-off board during long jumping (as in Lee et al., 1982) but while walking rather than sprinting. In some conditions, the room lights were intermittently extinguished either while the foot that would eventually land on the target was in swing phase or while that foot was on the ground. Subjects were successful in stepping on the target in both conditions, but movement trajectories were much less smooth when the room lights were off while the targeting foot was on the ground.

This is an important finding because it demonstrates that intermittent sampling is sufficient to precisely guide the foot to the target. It also suggests that the phase of the gait cycle during which visual information about an upcoming target is most important occurs when the foot that will land on that target is on the ground. Interesting to the authors, this preference to use information while the targeting foot is in the stance phase is so strong that if vision is briefly occluded during this phase, walkers will delay toe-off by slightly arresting forward momentum to ensure that they will see the upcoming target before the foot leaves the ground (Hollands & Marple-Horvat, 1996). This is all the more remarkable when one considers that walkers are capable of rapidly redirecting the trajectory of the foot during the swing phase if the location of the target unexpectedly changes (Barton, Matthis, Hinojosa, Brion, & Fajen, 2016; Hoogkamer, Potocanac, & Duysens, 2015; Reynolds & Day, 2005a). Despite having the capacity to execute rapid midflight responses, walkers clearly prefer to make adjustments while the targeting foot is on the ground.

In the aforementioned studies, the timing of visual occlusion was controlled by the experimenter. In the real world, choices about when to visually sample the upcoming terrain and when to sample other regions of interest are made by the walker. If visual information about a particular target is primarily used when the foot that will land on that target is in the stance phase, this preference should affect the characteristics of voluntary sampling of the visual environment. This prediction was tested by Patla, Adkin, Martin, Holden, and Prentice (1996) by instructing subjects to take several steps leading up to a region containing a target on which they had to step with their right foot. Subjects performed this task while wearing LCD goggles that they controlled by pressing a button to open and close the lenses. The instructions were to press the button to open the lenses when they deemed it necessary to perform the task. The main result was that subjects consistently sampled the visual environment before toe off of the right foot and rarely sampled the visual environment while the right foot was in the swing phase.

The degree of consistency in results across studies is quite striking given that each of the aforementioned studies was conducted by a different research group using different methods. Taken together, these studies provide clear and compelling support for the assertion that the information that is most useful for guiding foot placement on a given target is that which is available during discrete intervals of the gait cycle, specifically while the foot that will eventually land on that target is on the ground. Thus, walkers need not continuously sample information about the upcoming terrain. Intermittent sampling is sufficient.

Investigations of obstacle crossing lead to a similar conclusion about the needlessness of continuous sampling. Although stepping over obstacles demands precision in the placement of the feet in front of and behind the obstacle (Chou & Draganich, 1998; Muir, Haddad, Heijnen, & Rietdyk, 2015; Timmis & Buckley, 2012) and in the elevation of the feet over the obstacle (Patla & Rietdyk, 1993), such precision is not dependent upon continuous gaze fixation of the obstacle. When walkers do fixate an upcoming obstacle, they tend to do so two or more steps in advance and then shift their gaze to regions beyond the obstacle (Marigold & Patla, 2007; Patla, 1997). Of course, information from the lower visual field could still be sampled using peripheral vision (Franchak & Adolph, 2010; Marigold, Weerdesteyn, Patla, & Duysens, 2007) and used to continuously guide the feet. However, Timmis and Buckley (2012) found that when the lower visual field was occluded upon placement of the trail foot (i.e., the final step) before the obstacle, neither toe clearance during obstacle crossing nor placement of the lead foot on the far side of the obstacle were significantly different than when vision was unobstructed (see also, Buckley, Timmis, Scally, & Elliott, 2011; Mohagheghi, Moraes, & Patla, 2004; but see Patla (1998) for an inconsistent finding. This suggests that walkers are capable of using information picked up prior to the final step before the obstacle to control the feet over the obstacle—that is, continuous visual sampling is not needed during obstacle crossing.

Let us now return to the second part of the question posed at the beginning of this section—why is visual sampling intermittent? It is not because humans are incapable of adjusting the trajectory of the foot during the swing phase. When the situation demands rapid adjustment (e.g., because the intended target foothold unexpectedly changes location or because an obstacle suddenly appears), humans can redirect the trajectory of the swinging foot within as little as 120 ms (Patla, Prentice, Robinson, & Neufeld, 1991; Reynolds & Day, 2005b; Weerdesteyn, Nienhuis, Mulder, & Duysens, 2005). Nor is it because traversing extended stretches of complex terrain requires shifting gaze from the upcoming target to future targets, since peripheral vision could still be used to detect the information needed for online guidance of foot trajectory.

Instead of appealing to intuition, we could turn to theory to answer the question of why visual sampling is intermittent. Unfortunately, the perception-action coupling account of the early 2000s offers little help. While the account was flexible enough to accommodate different styles of control, it was agnostic when it comes to the question of why visual sampling and control are continuous in some circumstances and intermittent in others. This hole in the theory, as it existed in the early 2000s, is apparent in the de Rugy et al. (2002) model, which uses intermittent visual sampling and control by design. Had the theory at the time included a proper account of the "style" of coupling, intermittent sampling and control could have been an emergent property of the model rather than a feature that was added ad hoc to ensure consistency with the literature. Below, we explain how recent theoretical developments move us closer to a principled account of why visual sampling and control are not always continuous.

Question #2: How Do Control Strategies for the Visual Regulation of Gait Help to Ensure Energetic Efficiency and Stability?

The second question about the visual regulation of gait that motivates further theoretical development concerns how the control strategies that walkers adopt help to ensure energetic efficiency and stability. There is abundant evidence that when humans walk over flat, obstacle-free terrain, they move in a manner that is highly optimized with respect to metabolic cost. For example, although the efficiency of human locomotion varies with changes in gait parameters, energetic expenditure is generally least when humans are allowed to move at their preferred speed, stride rate, stride length, stride width, and type of gait (Donelan, Kram, & Kuo, 2001; Long & Srinivasan, 2013; Zarrugh & Radcliffe, 1978). When the normal way of walking is made less efficient (e.g., by having subjects wear a robotic exoskeleton that applies torques to resist certain movements), humans rapidly adapt to discover new, more efficient gait patterns (Selinger, O'Connor, Wong, & Donelan, 2015).

Not surprisingly, this preference for efficiency extends to the realm of complex terrain. Some key insights into the importance of energetic efficiency, as well as stability, have been gleaned by investigating how walkers select alternative footholds when the region of the ground on which the foot would normally land is deemed unsafe (Moraes, 2014; Moraes, Allard, & Patla, 2007; Moraes et al., 2004; Moraes & Patla, 2006; Patla, Prentice, Rietdyk, Allard, & Martin, 1999). In such situations, there are several factors that could, in principle, constrain the selection of an alternative foothold (e.g., minimization of changes to the ongoing gait cycle, maintenance of dynamic stability, continued locomotion without interruption). Given the multitude of factors, questions naturally arise about the process by which a single foothold is determined. Although this remains an open question, the existing data suggest that walkers choose options that ensure maintenance of forward progress as long as doing so does not come at a significant cost to stability or efficiency. This is the case when obstacles are detected several steps in advance because walkers can spread the energetic costs of the adjustment over several steps and they can make proactive movements to ensure that adjustments do not threaten stability. Indeed, when the obstacle is detected in advance and the terrain leading up to the obstacle allows for unconstrained foot placement, changes in foot placement begin to appear two steps in advance (Moraes et al., 2004).

However, if the obstacle is not detected until the last step, prioritizing forward progress may entail making adjustments that pose a greater threat to stability and efficiency (i.e., because it is not possible to spread the costs over several steps and because there is less time to make proactive movements to ensure stability). As a result, maintaining forward progress is less of a priority and walkers choose footholds that minimize foot displacement and do not threaten stability.[3]

For the present purposes, the important take-away from this previous research is that the control of locomotion on both simple and complex terrain is constrained by the need to minimize energetic expenditure and maintain stability (see also, Patla & Sparrow, 2000). As such, it would be reasonable to assume that the control strategies that walkers adopt for guiding foot placement on complex terrain help to ensure efficiency and stability. Nevertheless, strategies that were developed within the perception-action coupling framework offer little insight into how these factors constrain the control of walking. Such considerations have yet to be integrated into the perception-action coupling account.

Active and Passive Modes of Control

One of the most significant developments to emerge from the study of visual control in recent years is an understanding of how certain characteristics of behavior, such as stability, efficiency, coordination, and precision, can emerge without relying on perceptual information. This is referred to as passive control and is distinct from active control, which relies on perceptual information (Siegler, Bardy, & Warren, 2010). For the present purposes, the significance of this insight is that the active, perceptually guided control that epitomizes earlier accounts of visual gait regulation is not the only mode of control. As we hope to show, by expanding our account of walking over complex terrain to include both modes of control, we can better explain why walkers use visual information about the upcoming terrain during a particular phase of the gait cycle and how this strategy helps to ensure stability and efficiency.

The role of passive control in locomotion is intimately related to the dynamics that govern the movement of the body in the absence of active perceptual guidance. Studies of the kinematics (Mochon & McMahon, 1980), mechanics (Cavagna & Margaria, 1966), and energetics (Cavagna & Kaneko, 1977; Cavagna, Saibene, & Margaria, 1963; Cavagna, Thys, & Zamboni, 1976) of upright walking have shown that the dynamics of human locomotion are well approximated by a double pendulum. Under this description, the COM forms the bob of the first (inverted) pendulum, rotating about the ankle of the foot planted on the ground. The second bob is formed by the swinging leg, which rotates about the hip. The trajectory of this system through the course of a step can be accurately described by the initial state of the body before toe-off, and the movement during the step can be thought of as a physical object moving under its own momentum and the force of gravity (i.e., ballistic).

This description of human walking lends itself well to numerical modeling and analysis, and such efforts have culminated in surprisingly rich characterizations of bipedal locomotion from a relatively simple set of physical laws (McGeer, 1990). Indeed, even

[3] Interestingly, perceptual processes may also drive foot placement selection. For example, humans may choose footholds that are visually similar to previously stepped-on footholds, even if doing so requires a larger deviation of foot trajectory than would stepping on a visually dissimilar foothold (Fennell, Goodwin, & Burn, 2015).

the simplest of these passive dynamic walking models, whose behavior depends only on two parameters determined before toe-off, are robust in their approximations of the behavioral patterns and consequences of locomotion observed in real human data (Garcia, Chatterjee, Ruina, & Coleman, 1998). More important, these models capture a mode of locomotor behavior for which energetic efficiency and dynamic stability are consequences of the structure of the body, and which vastly outperform alternative modes of control on these metrics (Donelan, Kram, & Kuo, 2002; Kuo, 2007; Kuo, Donelan, & Ruina, 2005). Insofar as the human body possesses similar dynamics to those described for simple passive walkers, there is an opportunity for efficient, stable control of locomotion that emerges passively from the biomechanics alone.

The role of active, perceptually guided control is then to exploit these beneficial task dynamics by effecting changes in the parameters that govern the ballistic movement of the body on the upcoming step. This control strategy has been described previously as "mixed control" (because it combines the ideas of both passive and active control) and allows actors to reap the benefits of the passive dynamics of their body while retaining the flexibility and rapid response capabilities that characterize active perceptual control (Siegler et al., 2010; Siegler, Bazile, & Warren, 2013). In the case of locomotion, the parameters governing the ballistic movement of the body for the upcoming step are the location of the planted foot, which defines the base of the inverted pendulum for that step, and the push-off force from the trailing foot, which defines the initial COM velocity for the step (see Figure 1). Both

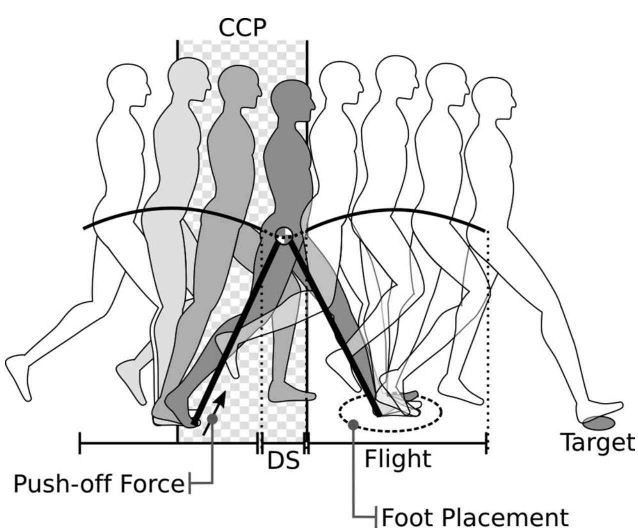

Figure 1. A depiction of the critical control phase for visually guided walking (Matthis, Barton, & Fajen, 2015, submitted). The ballistic trajectory of the center of mass (depicted as the circle superimposed over the middle figure) during the step to a target can be captured by two parameters—the place of the foot on the previous step and the push-off force generated at toe-off following double support (DS). Before toe-off, both of these parameters are under control of the walker, and the last point to make any adjustments to the parameters is during the last half of the preceding step (depicted here as the checkered background labeled CCP). Thus, the critical control phase (CCP) for visual control of foot placement is during the last half of the preceding step.

parameters are under the walker's control between the latter half of the previous step and the end of the double support phase. As such, successfully adjusting these parameters would require visual information during this period, which Matthis et al. (2015) referred to as the *critical control phase*.

Thus, we arrive at an explanation for why visual information is sampled during a particular phase of the gait cycle. Visual information about the upcoming terrain is intermittently (rather than continuously) sampled and is most relevant during the end of the preceding step because this is the critical phase of the gait cycle during which the parameters that govern the ballistic movement of the body are under the walker's control (Matthis et al., 2015; Matthis, Barton, & Fajen, 2016; Matthis & Fajen, 2013, 2014; see Figure 1). By using visual information to initialize the upcoming step and allowing the body to follow its natural trajectory, walkers can reap the benefits of stability and energetic efficiency that emerge from the physical dynamics of the body.

Experiment: Switching (or Not) to an Alternative Foothold

Although the convergence of this theoretical account with the observed behavioral data is compelling, the evidence of a preference among walkers to not interfere with the ballistic movement of the body when walking over complex terrain is indirect. A more direct approach to investigating this preference is to examine walkers' choices about which foothold to step on when more than one option exists for a given step. If perceptual control is organized around a desire to exploit the dynamics of the body during locomotion, then the detection of an alternative foothold should only influence foot placement selection if switching to the new foothold would not interfere with the ongoing ballistic movement of the body. The present experiment was designed to test this prediction.

Approach

Subjects were instructed to walk over a series of virtual "stepping stones" that were projected onto the floor (see Figure 2a). Five of the six stepping targets were positioned equidistant along the path and their spacing was scaled to the preferred step length for each subject (Donelan et al., 2002). The remaining target (the fourth in the set) was incongruent with the rest of the targets insofar as it required subjects to make a significant adjustment to step length and/or width. At some point after the subject began walking but before he or she reached the incongruent target, another target appeared in the vicinity of the incongruent target but in a position that was congruent with the rest of the path, affording subjects a choice about where to step (see Figure 2b and 2c). The timing of the appearance of this congruent target was randomly manipulated on each trial such that it could appear as early as when the subject was two steps away and as late as when the step to the fourth target was almost completed. This paradigm was inspired by the one used by Brenner and Smeets (2015) in the context of pointing with the finger.

Rational and Predictions

Choosing to step on the incongruent target required a significant change in step length and/or width relative to the subject's pref-

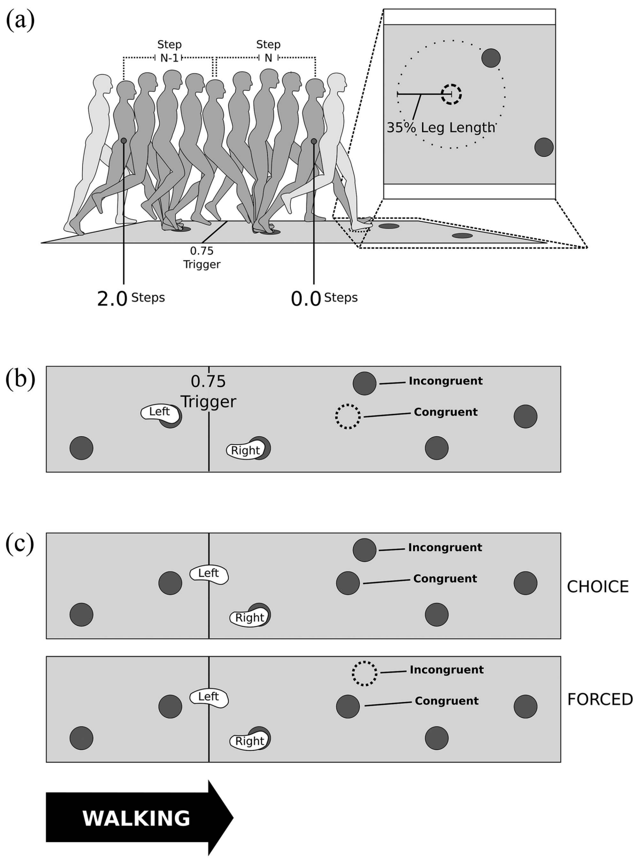

Figure 2. Experimental environment setup and manipulation. (a) Subjects walked across a field of stepping targets. At different points during their gait cycle (depicted here using the dark gray human forms) either a choice or forced switch would be triggered. These stimulus triggers were drawn from 0.0 to 2.0 steps (in terms of the gait cycle) in advance of the step to target *N*, and were triggered by either the left or right foot. (b) Top down view of setup, with a single trigger (~0.75 steps) represented. Initially only the incongruent target on Step 4 was present. (c) Top: Choice condition where a choice was required once the trigger as activated. Bottom: Forced condition, where a switch was required once the trigger was activated.

erence, not only on the step to the incongruent target but on the next two steps as well. For example, incongruent targets that required a lengthening of the step would leave subjects in a position to have to shorten their steps to the next two targets. It seems intuitive that steps to incongruent targets should be more effortful and possibly less accurate. As such, one would expect that on trials in which the congruent target appeared when the subject was far away (e.g., 1.5 to 2.0 steps ahead), the congruent target would be the dominant preference for where to step.

Likewise, on trials in which the congruent target does not appear until the subject is within 0.5 steps, switching to the congruent target would require one to rapidly redirect the trajectory of the foot. Such last-moment, midflight adjustments could disrupt stability and affect the accuracy and precision of foot placement. As such, it also seems intuitive that subjects would prefer to step on the incongruent target on trials in which the congruent target does not appear until the targeting foot is almost halfway through the step.

The critical question for this experiment is how far in advance does the existence of an alternative target in the congruent position need to be made apparent before the subject prefers to switch to that target rather than remain with the incongruent target? If walkers have a strong preference for moving ballistically through a step, then the choice of which of the two targets to step on should depend on when the congruent target appears relative to when the control parameters of the body's ballistic trajectory are under the walker's control (i.e., the critical control phase). Given that these parameters are adjusted toward the end of the previous step (Matthis et al., 2015; Matthis & Fajen, 2013), subjects should prefer the incongruent target (i.e., not switch) unless the congruent target becomes visible before the step is initiated.

Alternatively, walkers may not have a particular preference for moving ballistically but rather a strong preference to step on targets that minimize changes in step length or width relative to previous steps. If so, subjects should prefer the congruent target as long as it appears early enough for them to successfully hit the target. In other words, the choice of which of the two targets to step on should depend on when the congruent target appears relative to the last moment at which subjects are capable of landing on the congruent target without loss of accuracy. Given the evidence from previous studies (Reynolds & Day, 2005a, 2005b; Weerdesteyn et al., 2005) that humans can execute rapid and accurate changes to foot placement even after a step has begun, subjects would be expected to switch to the congruent target except on trials in which that target does not appear until after the step is significantly underway. To allow for a more specific prediction, we included a second session in our experiment in which subjects were forced to switch to the congruent target when it appeared during their approach (i.e., the incongruent target disappeared, leaving no choice). This allowed us to measure each subject's ability to rapidly redirect the foot to the congruent target, which we then compared with their preferences for congruent and incongruent targets when both were available.

Method

Participants

Seventeen subjects (6 women; age [M = 19 years, range = 18–20 years]) were recruited from an undergraduate psychology course and received course credit for their participation. None reported having any visual or motor impairments. Two subjects were excluded from the analysis because of problems with the motion capture process during experimentation. Two additional subjects were removed during the analysis when it was discovered that their motion capture data were corrupted. This left a total of 13 subjects who were successfully included in the analysis.

Equipment Setup

This study utilized a 14-camera, passive motion-capture system from Vicon, running Vicon Nexus 1.8 software. This system tracked the positions of 34 retro-reflective markers attached to a tight-fitting elastic suit worn by subjects. Markers were positioned on subjects' bodies following the Plug-In Gait Full Body (SACR) kinematic model provided with the Vicon software. A BenQ MW853UST+ ultra short-throw projector was used to display a field of virtual stepping targets onto the ground, forming a path across which subjects were asked to walk. The projector's resolution was $1,280 \times 800$ with a brightness of 3200 ANSI lumens. The projector was positioned parallel to the walking path, creating a projection approximately 5 m in length. The projector was mounted on a heavy-duty tripod and oriented perpendicular to the ground. Because of the auto key-stoning nature of short-throw projectors, no key-stoning algorithm was required. However, a custom algorithm was used to align the coordinate frame of the motion capture system with the origin of the projected virtual world. This algorithm used a simple RMSE minimization procedure to find the rotation matrix that aligned the motion-capture and projector coordinate frames.

Virtual Environment and Task

The environment consisted of a path of six virtual stepping targets (Figure 2a). Targets were positioned such that the distance between the targets in the direction of locomotion correspond with measurements of preferred step-length, calculated to be $0.7 \times$ Subject leg-length (Kuo, 2001). The distance between the stepping targets (along the medial/lateral axis) was set at $0.35 \times$ Subject leg length. While this is larger than the preferred step-width that has been measured for walkers traversing flat terrain (Donelan et al., 2001), the adjustment was necessary for the manipulations described below and no subjects reported issues or discomfort reaching the target footholds. On each trial, we pseudorandomly selected which foot (left or right) subjects would use to take their first step, ensuring that each subjects started with the left and right foot an equal number of times in each block. Subjects stepped to the first target from a stationary position, and reached steady state walking speed by the end of the step to the second target.

On the majority of trials (see below), the fourth target in the series was positioned at a randomly selected position along a circle of radius equal to 35% of subject leg-length centered on the location of a target that would be congruent with the path (Figure 2a–b). This "incongruent target" represented a significant stepping deviation from the congruent target position and required subjects to make an abnormally narrow, wide, long, or short step.

Subjects began each trial in a defined start box. When they received a "go" signal from the experimenter, they pressed a button on a wireless remote held in their hand that began the trial. After this button press, a whistle signaled to subjects to begin walking. Subjects were instructed to walk across this path stepping on the targets as accurately as possible. Accuracy was defined as the distance between the reflective marker on the proximal joint of the second toe and the center of a target. Subjects had 6 s to complete their walk or the trial would reset and they would be required to redo the trial. This time limit provided a hard limit on walking speed for all subjects, preventing them from slowing across trials. Each trial concluded when subjects crossed into an end zone located at the far edge of the projection volume from where they began.

Because of the processing time and network communication used within this setup to enable communication between the motion capture system and the virtual environment, there was a constant lag between subject actions and the results within the virtual environments. We measured this lag to be between 80 and 90 ms on average. Because this lag was constant, we were able to account for this issue by applying a fixed increase of 15% of a step to each trigger that controlled the presentation of the choice or forced switch. Thus, the appearance of a target halfway through the step (0.5 steps in advance) was produced by creating a trigger that was activated when the system measured the subject to be at 0.65 steps in advance. The values selected for this correction were based on previous work using similar setups (Matthis et al., 2015; Matthis & Fajen, 2013) as well as measurements taken during pilot testing for this study. One consequence of this setup is that occasionally choices or switches may have been provided earlier than the reported maximum of 2.0 steps. However, these occurrence were rare and when they did occur, the resultant trigger that was used to control the presentation of stimuli was very near the intended maximum. To account for variability introduced in the timing of triggers by these hardware factors, analyses and results refer to the effective triggers (i.e., those triggers which actually occurred as measured after experimentation).

Design

Each experimental session comprised two blocks (Choice and Forced) of 150 trials, with all subjects completing the Choice block first. One hundred of the 150 trials per block were control trials on which subjects were not presented with a choice about where to step or forced to switch from one target to another; that is, there was one and only one target for each step and the targets did not change position during the trial. On 90 of the 100 control trials in each block, the fourth target was incongruent with the other targets and in the remaining 10 control trials, the fourth target was congruent with the other targets. For all trials, subjects were instructed to step as precisely as possible by placing the ball of their foot as near to the center of the target as they could. However, we also asked them to maintain a brisk walking pace during the experiment (enforced by a 6 s time limit on each trial) and to a step as "normally" as possible by avoiding behaviors like tip-toeing or hopping from target to target. A warm-up period was provided at the start of the experiment to allow subjects to experience the environment and provide the researchers with an opportunity to correct any misunderstandings about these instructions.

The remaining 50 trials in each block were the manipulated trials in which subjects either had to make a choice about where to step (in the Choice block) or were forced to switch from the incongruent target to the congruent target (the Forced block). Control trials and manipulated trials were shuffled pseudorandomly within each block so that subjects could not predict on any given trial whether or not a choice/forced switch would be required. In the Choice block, a second target appeared in the congruent position for the fourth step, offering subjects a choice about where to place their foot (i.e., on the incongruent target or the congruent target). Subjects were instructed to step on the target that felt most comfortable, natural, or easiest to reach when provided with a choice. Several choice trials were included in the warm-up before data collection, providing subjects with an opportunity to become comfortable with this decision making paradigm.

The timing of the appearance of the congruent target was varied as a function of the distance of the walker from the incongruent target, in units of steps. The specific value of this timing was pseudorandomly selected on each trial from a range of 0.0 steps to 2.0 steps (Figure 2a). For example, if the choice on a particular trial was presented at 0.75 steps (as in Figure 2b), the congruent target would become visible when the foot had crossed a 25% of the distance required to reach the target. Choices that were presented at a distance of greater than one step occurred during the preceding step or during the double support phase. If, for this same target, the choice instead was presented 1.5 steps in advance, then the congruent target would appear halfway through the swing phase of the previous step (i.e., when the right foot was halfway to the previous target).

Manipulated trials in the Forced block were similar to those in the Choice block with the exception that the incongruent target disappeared at the moment that the congruent target appeared (Figure 2c). As in the Choice block, the timing of the change was manipulated within a range of 0.0 to 2.0 steps. Subjects were instructed to do their best to step on the target if its position changed. This protocol was approved by the Institutional Review Board (IRB) at Rensselaer Polytechnic Institute and complies with the guidelines set down in the Declaration of Helsinki.

Analyses

Data were postprocessed using custom Matlab code. These procedures formatted the raw data, temporally aligned motion capture and projector data, and output the appropriate data structures for statistical analysis. After this post processing, statistical analyses were conducted using the R statistical programming environment (R Core Team, 2016). All analyses and procedures described below were conducted in R.

To understand how subjects selected their preferred stepping target, it was necessary to quantify the frequency with which they stepped to both congruent and incongruent targets as a function of when the incongruent target was made available. Because subjects sometimes missed the target and stepped on a location between the two targets, it was not always immediately obvious which target they intended to step on. We created a decision criterion for classifying steps to congruent and incongruent targets based on the expected foot placement and variability in control conditions where no choice was presented. To assess which target subjects intended to step on (regardless of whether or not they were successful), we fit a loess (R Core Team, 2016) regression (span = 0.75, degree = 2) to subject data from control trials in which only the incongruent target was present. Modeling absolute distance from the center of the congruent target position as a function of foot placement angle. Using this model, we defined a cutoff boundary to be twice the standard deviation of the model prediction for a given angle below that predicted value. In this way, our threshold for determining which target subjects were attempting to reach accounted for potential differences that might depend on the position of the incongruent target relative to the congruent target. It also accounted for differences in the variability of stepping accuracy that may exist between congruent and incongruent targets. If not accounted for, such differences can lead to unwanted biases and misclassifications (see Fennell, Goodwin, Burn, & Leonards, 2015 for a discussion of a conceptually similar method). Foot placement that resulted in distances from the center of the congruent target that fell below the threshold were considered steps to the congruent target. Steps that resulted in distance metrics above the threshold were considered steps to incongruent target.

The primary independent variables manipulated in this study were the point at which the congruent target was made visible and the angle at which the incongruent target was positioned relative to the congruent target position (here on referred to as the *target angle*). Both of these variables were selected pseudorandomly from a continuous distribution independently for each subject. Therefore analyzing these data was done using linear mixed effects models with subjects as random factors. We also used paired *t* tests to compare subject differences across the choice and forced conditions in the experiment. Details of the specific analyses and statistics used can be found with the appropriate results.

We also investigated the degree to which the movement of subjects' COM could be modeled as an inverted three-dimensional (3D) pendulum. As the benefits afforded by the biomechanical structure of the body depend on exploiting one's pendular dynamics, quantifying how "pendulum-like" a step is provides an indication of how much one's biomechanical structure is being leveraged. Further, we can evaluate how changes in the visual information available affect how much the biomechanics are being exploited.

For every step to the fourth target taken by subjects, we used the position and velocity of the center of mass at toe-off, and the position of the supporting leg, as the initial condition for a numerical simulation of a 3D pendulum falling passively. We then calculated the deviation of the actual trajectory of the COM from this predicted trajectory by summing the Euclidean distance between the trajectories over the course of the step. This method was adapted from Matthis and Fajen (2013). We used the control condition in which no manipulation was present and the congruent target was always visible as our baseline for the most pendular walking behavior available within the context of our design. We then subtracted mean subject deviations in these control conditions from every trial to create a centered measure of COM deviation relative to the control condition.

Results

Preliminary Analyses

The logic of the experiment rests on the assumption that when subjects are given a choice to step on the congruent target or the incongruent target, and both targets are plainly visible far in advance, there will be a preference for stepping on the congruent target. This assumption was confirmed by examining foot placement selection on the 10 trials (per subject) within the choice block on which the congruent target appeared earliest. For these trials, the congruent target appeared as early as 2.01 steps in advance and no later than 1.54 steps in advance. Using the procedure described in the analysis section for determining which target subjects intended to step on, we found that the mean proportion of trials on which subjects chose the congruent target was 0.80 (95% confidence interval, CI = 0.1). This confirms that had both options been present from the start, subjects would have overwhelmingly stepped to the target that was congruent with the defined path.

Why Did Subjects Prefer Congruent Targets?

Although it seems intuitive that subjects would prefer the congruent target when both options are visible far in advance, the reason for this preference is less obvious. One might assume, for example, that the congruent target is preferred because foot placement is less accurate when stepping on the incongruent target. This seems plausible given that incongruent targets required a significant break from each subject's preferred stepping characteristics. At first glance, it would seem that evaluating this explanation is simply a matter of comparing absolute stepping error on the two types of control trials (i.e., those in which the fourth target was in the congruent position vs. those in which the fourth target was in the incongruent position). However, this overlooks the fact that the angle of the incongruent target was randomized (see Figure 2a), which could affect the difficulty of accurately stepping on that target as well as the subsequent (i.e., fifth) target. As such, it was necessary to examine stepping error on incongruent control trials across the range of target angles and for both the fourth and fifth targets.

First, we grouped steps to incongruent targets for all subjects into 18° bins based on the angle at which the incongruent target appeared relative to the congruent target position. We also reflected all right foot steps across the midline, such that for all incongruent targets, 0, 90, 180, and 270° corresponded to anterior, medial, posterior, and lateral positions (respectively) relative to the congruent target position. We then calculated the mean absolute stepping error within each of these 18° bins (see Figure 3a). As expected, stepping error varied with the angle of the incongruent target. Specifically, there was a tendency for stepping error to be greater for incongruent targets that were positioned anterior and lateral to the position of the congruent target. The magnitude of stepping error in these conditions often exceeded the radius of the target (0.05 m), which means that subjects often missed targets located in this range of directions. In contrast, stepping error for targets that were positioned medial and posterior relative to the congruent target was lower and below 0.05 m. A linear mixed effects analysis (Bates, Mächler, Bolker, & Walker, 2015), with the angle of the incongruent target[4] used to predict stepping error, was used to measure the effect visible in Figure 3a. We found a small but significant effect of target angle on stepping error based on a log-likelihood comparison to a null model that did not account for target angle ($\chi^2 = 24.181$; $p < .001$; $\Omega^2 = 0.075$).[5] These results are summarized in Table 1.

Mean absolute stepping error for congruent targets on control trials was 0.045 m (95% CI = 0.010). So although subjects were less accurate when stepping to incongruent targets in the lateral and anterior directions, stepping error for incongruent targets in medial and posterior directions was comparable to error for congruent targets. This is most likely because of the fact that the linear distance from the previous (i.e., third) target is larger for lateral and anterior directions and smaller for medial and posterior directions.

Although incongruent targets were relatively easy to hit when they were located in medial and posterior directions, the distance to the next (i.e., fifth) target was greater. If it is indeed the case that targets requiring greater reach lead to increased stepping error, then incongruent targets that were closest to the previous step (i.e., medial and posterior oriented targets) should induce greater stepping error on the subsequent step as the distance between the fourth and fifth target is greater in this case. Indeed we saw a tendency for stepping error on the fifth target to be greater when the incongruent target on fourth step was positioned medial and posterior relative to congruent target position (Figure 3b).

To summarize, although subjects were less accurate when stepping on the incongruent target in some conditions, foot placement accuracy in other conditions was comparable with that for congruent targets. Furthermore, the effect of the incongruent target was sometimes more apparent in the accuracy of foot placement on the subsequent target. Based on these findings, it seems unlikely that the strong preference for congruent targets reported above simply reflects a propensity to step on the target that can be hit more accurately. In the Discussion, we will consider alternative explanations, including the possibility that subjects preferred the congruent target because it minimized the need to interfere with the ballistic trajectory of the COM.

Stepping Preference and Ability

Having confirmed that the assumed baseline preference for the congruent target was evident, the next question is how this preference to switch to the congruent target depends on when that target becomes visible. We characterized each subject's choice of targets as a function of when the choice was presented (in units of step). For each subject, a logistic regression model was fit to the foot placement choices that were recovered using the thresholding procedure described in the analysis section. Figure 4a illustrates the data and model for one example subject. Using these logistic models, we were able to characterize the point at which the likelihood of switching from the incongruent target to the newly visible congruent target was at chance (.5 probability). Choices that were presented before this chance point were more likely to result in subjects switching to the congruent target. Choices that were presented after this point were more likely to result in subjects disregarding the new alternative and maintaining their intention to step on the incongruent target.

We found that on average subjects were more likely to switch to the congruent target if the choice was presented before 1.21 steps (95% CI = 0.21). In other words, subjects reliable switched to the congruent target when the option was made available well before the end of the preceding step. However, when the congruent target appeared after this point, subjects tended not to switch—that is, they maintained their preference for the incongruent target.

The fact that subjects preferred to step on the incongruent target even when the congruent target appeared before the step was initiated is consistent with a strong preference to move ballistically; that is, to allow the body to follow its natural, pendular trajectory without neuromuscular intervention. However, before any strong conclusions can be drawn, it is necessary to rule out an

[4] In this case, we broke the angle of the incongruent target into its sine and cosine components and use these each as independent predictors. This serves to make the regression linear in polar coordinates, such that the model correctly accounts for error across the 0°/360° boundary.

[5] While measuring effect size for mixed effects models is not intuitive or straightforward, Xu (2003) provides an equivalent term (Ω^2) that quantifies the variance explained by the full mixed effects model relative to a simplified model that depends only on the intercept, and scales in a manner similar to R^2 in fixed effects models.

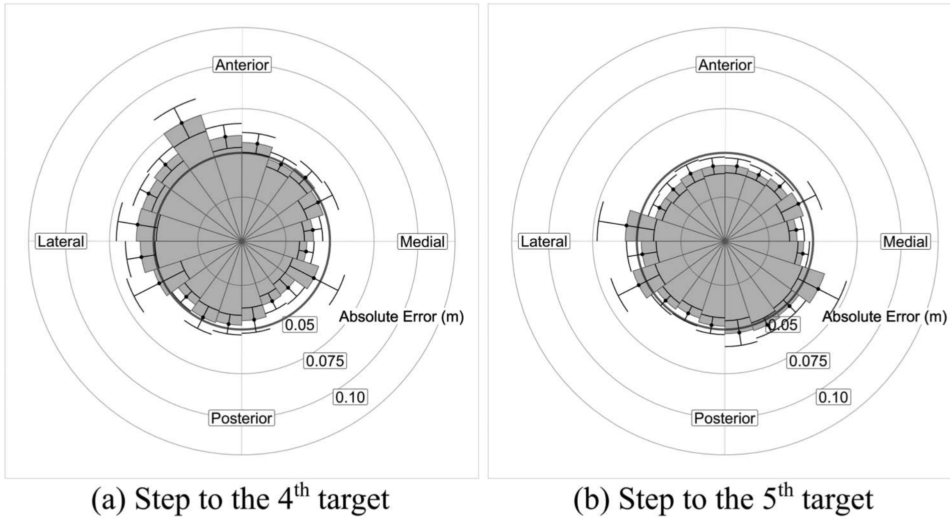

Figure 3. Polar plots showing the distribution of stepping errors across different angles of the incongruent target relative to the congruent target. Each bar represents mean absolute stepping error for all steps to incongruent targets in an 18° bin. Error bars are 95% confidence intervals. The thick dark circle marks an absolute error of 0.05 m, which is the outside edge of each stepping target. (a) Absolute stepping error on the 4th target for incongruent target angles. (b) Stepping error on the 5th target (i.e., the target after the incongruent target) for different incongruent target angles on the 4th target.

alternative explanation—that subjects chose not to switch to the congruent target even when it appeared shortly before toe-off simply because they did not have sufficient time to redirect the foot to the congruent target.

To evaluate this alternative, we conducted a breakpoint analysis by applying a segmented linear regression (Muggeo, 2003, 2008) to stepping error data from the Forced block, in which subjects were forced to switch from incongruent to congruent targets. A segmented linear regression attempts to find N linear functions that apply across a predictor variable to minimize the total root mean squared error (RMSE). As this is a potential gateway to overfitting, model comparisons using Bayesian information criterion (BIC) penalize high numbers of linear models. The greatest decrease in BIC was observed with the addition of a single breakpoint for all subjects (mean BIC decrease = −32.45; 95% CI = 11.13). We used a Davies test (Muggeo, 2008) to verify that the slopes of the two fitted linear models for each subject were significantly different. For all subjects, two linear models with significantly different slopes were found to capture the relationship between when the switch from incongruent to congruent targets occurred, and the stepping error observed after the switch. Further, linear models fit before the breakpoint (i.e., when the target switched from the incongruent to congruent position early on) had negligible slopes, suggesting there was little to no relationship between when the switch occurred and the observed stepping error (mean slope = 0.02, 95% CI = 0.009; mean R^2 = 0.031). Models after the break showed a significant relationship between the timing of the switch and the observed stepping error (mean slope = 0.41, 95% CI = 0.06; mean R^2 = 0.09). The nature of these models indicates that changing the possible stepping target from the incongruent to the congruent position only affected stepping error after the step to the target was well underway.

Figure 4b shows the fitted segmented linear models for one example subject. On average, subjects were able to maintain stepping accuracy when the switch occurred before 0.88 of the step to the upcoming target (95% CI = 0.09). That is, when subjects were forced to switch from the incongruent target to the congruent target, they were able to accurately redirect the foot without a drop-off in accuracy even if the congruent target did not appear until shortly after toe-off. This confirms that subjects were capable of using visual information during the step to make adjustments to foot placement if necessary.

Because the direction at which the incongruent target was oriented had an effect on stepping error in control conditions, it is possible that the error observed after the breakpoint was also affected by the target angle of the incongruent target. We investigated this possibility by conducting a linear mixed effects analysis (with subject as a random factor) on steps that occurred after the mean breakpoint, comparing models with and without the angle of the incongruent target as a factor for stepping error using log likelihood. The results are reported in Table 2. Ultimately, although the angle of the incongruent target has some persistent effect, this effect was not found to be a factor in stepping error when subjects were forced to make a switch ($\chi^2(1)$ = 0.187, p = .91).

The analysis of stepping error in the Forced block clearly indicates that subjects were capable of switching to the congruent target without a drop-off in accuracy even if that target appeared shortly after the step to the incongruent target was initiated. Thus, if subjects prefer targets that minimize changes in step length or width relative to previous steps, the critical distance (in steps) at which they were equally likely to choose both targets should have been around 0.88. However, a comparison of preferred decision points to breakpoints in stepping accuracy reveals that subjects

Table 1
Effect of Incongruent Target Angle (φ on Error in Control Trials

R model formula: Absolute error ~ *Sin*(ϕ) + *Cos*(ϕ) + ϵ

ϵ = (1 + Sin(φ) + Cos(φ))|Subject + Residual

Group	Name	Variance	*SD*
	Random effects		
Subject	Intercept	.02321182	.07729859
	Cos(ϕ)	8.796e-06	.002966
	Sin(ϕ)	9.994e-06	.003161
Residual		1.757e-03	.041920

	Estimate	*SE*	*t* Value
	Fixed effects		
Intercept	.050635	.002073	24.423
Cos(ϕ)	.008770	.001474	5.951
Sin(ϕ)	−.008498	.001516	−5.604

Ω^2	Bayesian Information Criterion (BIC)	Deviance	Residual *df*
.07478427	−8082.1	−8159.6	2,326

	df	BIC	Deviance
	Model comparison		
Intercept only model	8	−8073.4	−8135.5
Mixed effects model	10	−8082.1	−8159.6
	df	Value	
χ^2	2	24.181	
p		5.61e-06	***

*** $p < .001$.

preferred to switch only when visual information about the alternative was present significantly before the point at which they could no longer reach the new target, $t(12) = 3.32$, $p = .006$; Cohen's $d = 1.24$. Figure 5 shows the box plots for the distribution of decision points (Choice block) and breakpoints (Forced block). In addition to the differences in the mean, we can see that the decision points are much more variable than the breakpoints, suggesting that other factors that are subject dependent may have influenced where walkers decided to step. Thus, we can rule out the possibility that subjects chose not to switch to the congruent target even when it appeared shortly before toe-off simply because they did not have sufficient time to redirect the foot to the congruent target. The hypothesis that walkers prefer targets that allow them to move ballistically throughout the step provides a more complete account of the findings.

Stepping Preference and COM Trajectory

To further explore whether a preference to move ballistically underlies subjects' choices about which target to step on, we conducted an analysis of the trajectory of the COM during the step to the fourth target. First, let us consider trials in the Choice block in which the congruent target appeared too late for subjects to reliably prefer to switch to that target but early enough for subjects to accurately step on that target if they had to. We refer to this as the "middle" interval and defined its boundaries for each individual subject using the inflection point and breakpoint that were calculated in the previous analysis (see Figure 6).[6]

On such trials, subjects more often stepped on the incongruent target but sometimes stepped on the congruent target. By our account, subjects preferred the incongruent target because they had already initialized (or started to initialize) the upcoming step to hit that target. As such, switching to the congruent target was less desirable because it would require a midflight adjustment that interferes with the passive trajectory of the body. If this account is correct, the trajectory of the COM should deviate farther from that of a passively moving inverted pendulum when subjects stepped on the congruent target compared with when they stepped on the incongruent target.

To test this prediction, we analyzed the degree to which the trajectory of the COM during the step to the fourth target of each trial deviated from that of a passively moving inverted pendulum. The latter was estimated by simulating a model of an inverted pendulum in 3D. For each trial, we fed the initial position and velocity of the subject's COM at the beginning of the step to the 4th target and ran the simulation for a duration equal to the duration of that step. We then measured the cumulative deviation between the predicted and actual COM trajectories. The smaller the difference, the more similar the subject's movement is to that of a passively moving inverted pendulum (see Analysis section of Method for additional details).

Figure 7 shows the cumulative COM deviation as a function of the interval during which the congruent target appeared, broken down by the target to which the subject stepped (congruent, incongruent) and the block (Choice, Force). Values of the dependent measure were centered to each individual subject's cumulative COM deviation on control trials in which only the congruent target was visible. As expected, the mean cumulative COM deviation was greater on trials from the middle interval when the subject chose the congruent target compared with the incongruent target (see Figure 7a and 7c). In contrast, the mean cumulative COM deviations on steps to congruent and incongruent targets were more similar when the congruent target appeared earlier, which makes sense because subjects had sufficient time to properly initialize the upcoming step regardless of which target they chose to step on. Likewise, the difference in cumulative COM deviation was more pronounced when the congruent target appeared later, which can be attributed to the greater need for midflight corrections. Note that this analysis was exploratory; that is, it was not planned before data collection. As such, we refrained from running any classical tests of statistical significance and we caution readers that our interpretation must be considered preliminary. With that in mind, this analysis provides converging evidence in support of the hypothesis that walkers choose targets that they can step on by minimally intervening with the passive COM trajectory.

The data from the Forced block also support this interpretation. When the change in target position occurred early, subjects were able to hit the congruent target without interfering with the COM trajectory any more than they did on trials in the control condition

[6] Data from three subjects were excluded from this analysis because their inflection points were smaller than their breakpoints. Hence, the three intervals defined in Figure 6 do not exist for these subjects.

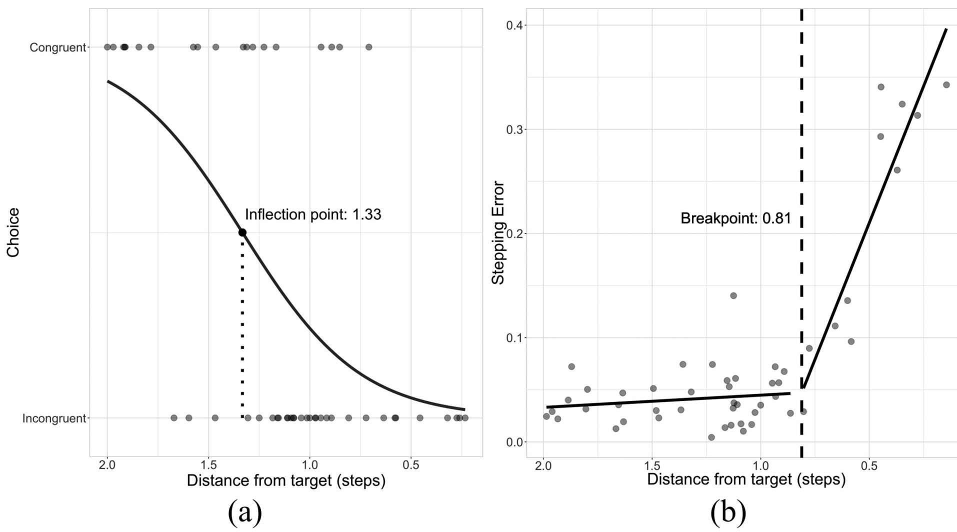

Figure 4. Example data for one representative subject. (a) *Choice* condition where subjects either switched to the congruent target (top) or did not (bottom). Using a logistic regression on the decisions made by the subject on each trial (as a function of when that choice was presented) we are able to find the inflection point, which indicates the point at which the subject is equally likely to switch as to not switch. (b) Absolute stepping error for the *Forced* condition as a function of when the change in the availability of the incongruent and congruent targets occurred. Segmented linear regression was used to identify the point at which subject error began to increase.

when only the congruent target was present (see Figure 7b). However, when the switch occurred during the middle or late intervals, the cumulative COM deviation was greater than it was in the control condition.

Discussion

When humans walk over complex terrain, they often have more than one option about where to place their foot on each step. Sometimes, however, the different possible footholds for a given step become visible at different times as the walker advances. Our discussion of the results is organized around two scenarios: (a) when all of the possible options are apparent to the walker well in advance, and (b) when a walker initially perceives that there is only one foothold for a given step but later detects that an alternative option exists. As we hope to explain, the results suggest that in both scenarios, walkers' choices about where to step are strongly influenced by a preference for moving ballistically.

Where do Walkers Prefer to Step When All Possible Options Are Visible Well in Advance?

On a subset of trials completed by each subject, visual information about the two different foot placement options was provided far in advance of the step where the choice was actually required. When the congruent target appeared during the first half of the preceding step (i.e., before 1.5 steps in advance), subjects were afforded ample time to detect the availability of a novel option and execute a change in trajectory if they desired. We found that under such conditions, subjects overwhelmingly preferred the target that was congruent with the rest of the path.

This preference for stepping to congruent targets cannot be explained by a propensity for targets that can be hit more accurately, as only steps to incongruent targets positioned anterior and lateral to the congruent target resulted in increased inaccuracy. Walkers may, however, take into account the impact that placing the foot in a particular location has on their accuracy on subsequent steps. Indeed, we found evidence suggesting that such interstep dependence is a relevant factor, as the direction of an incongruent target (relative to the congruent target position) impacted subjects' stepping accuracy on both the step to that target and the subsequent step. If walkers are sensitive to not only the feasibility of the immediate step being executed, but also the effect that that step may have on future steps, congruent steps may be preferred overall because they balance reachability with the ability to take successful future steps.

Congruent targets may offer some additional benefit besides being less prone to error—they may allow walkers to minimize deviations from the passive ballistic trajectory of the body that emerges from the dynamics of locomotion. In general, the pendular dynamics of walking that prescribe the ballistic motion of the body are dynamically stable, providing a natural buffer against small perturbations (e.g., small variations in foot placement). From one step to the next, the momentum of the COM is largely conserved and trajectories of the COM during the step are highly regular, as the condition of the body at the end of a step provides the initial conditions for a passively stable movement trajectory on the subsequent step (Garcia et al., 1998; Roos & Dingwell, 2011). However, the gradual decay of error because of dynamic stability alone may not be sufficient to correct for large deviations in foot placement, such as steps to incongruent targets. While walkers may be able to make adjustments to the initial conditions of a step

Table 2
Effect of Incongruent Target Angle (ϕ) on Error in Control Trials

R model formula: Absolute error ~ Distance from target + ϵ

ϵ = 1|Sin(φ) + 1|Cos(φ) + 1|Subject + Residual

Group	Name	Variance	*SD*
Random effects			
Sin(aϕ)	Intercept	.0003180	.01783
Cos(ϕ)	Intercept	.0003718	.01928
Subject	Intercept	.0004785	.02187
Residual		.0052588	.07252
	Estimate	*SE*	*t* Value
Fixed effects			
Intercept	.37972	.01709	22.21
Distance from target	−.34815	.02794	−12.46
Ω^2	Bayesian Information Criterion (BIC)	Deviance	Residual *df*
.6345852	−346.5	−377.3	163
	df	BIC	Deviance
Model comparison			
Sin(ϕ) and Cos(ϕ) not included	4	−356.60	−377.12
Sin(ϕ) and Cos(ϕ) as random factor	6	−346.53	−377.31
	df	Value	
χ^2	2	.1868	
p		.91	

to produce a ballistic movement to an incongruent target (so long as it is visible far enough in advance), such a change almost certainly would then necessitate adjustments to the initial conditions of the subsequent step to return to the congruent path. Instead, walkers may control stepping in a manner that minimizes variability to the trajectory of the COM during locomotion and choose footholds that minimize the adjustments that must be made to the initial conditions of any particular step.

This provides a strong motivation for walkers to select footholds that minimize the deviation of the COM trajectory from the biomechanically prescribed motion (i.e., from the ballistic trajectory of the body), and thus prefer congruent stepping targets. Such a control strategy can be thought of as keeping behavior near the middle of the stable basin of attraction that is defined by the mechanical properties of the body for each step, maximizing the utility of inherent dynamic stability. This method of control has been shown to underly other motor tasks that possess similar dynamic properties to locomotion. Bouncing a ball on a paddle, for example, is a periodic, dynamically stable behavior that has passively stable modes defined by the mechanical properties of the system involved (Schaal, Atkeson, & Sternad, 1996; Sternad, Duarte, Katsumata, & Schaal, 2001). Humans performing this task actively use visual information to keep behavior near the stable basins of attraction defined by the task dynamics (Siegler et al., 2010, 2013).

In the context of locomotion, advantageous dynamic properties (like stability) are a product of the pendular mechanics of the body.

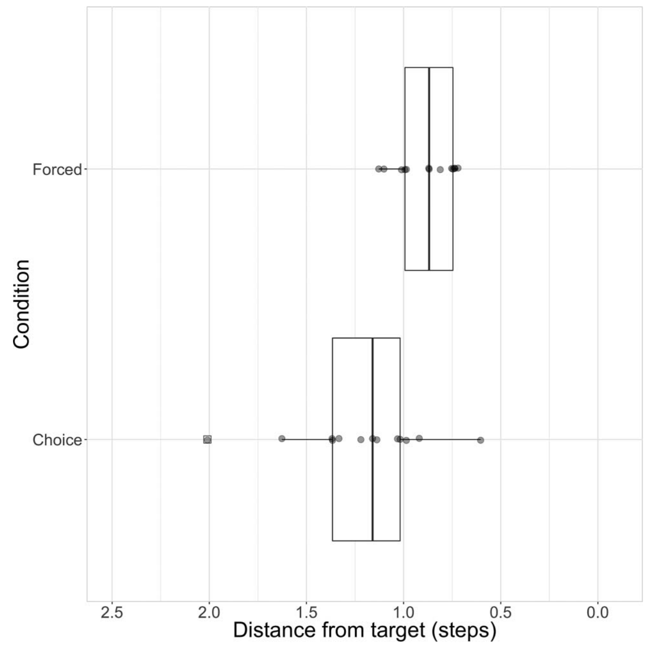

Figure 5. Box plots showing median, and 1st and 3rd quartiles, for breakpoints (in the *Forced* condition) and inflection points (in the *Choice* condition). A paired *t* test confirms significant differences in these data, indicating that the point at which subjects choose to switch is not the same as the point at which they are capable of successfully switching if forced.

Therefore, if walkers are using a control strategy that seeks to utilize these advantageous qualities, the selection of footholds is likely to be dependent on maintaining the progression of (rather than interfering with) these dynamics. An interesting find was that a broad strategy of "maintain forward movement of the body" has been proposed to explain findings of previous studies of alternate

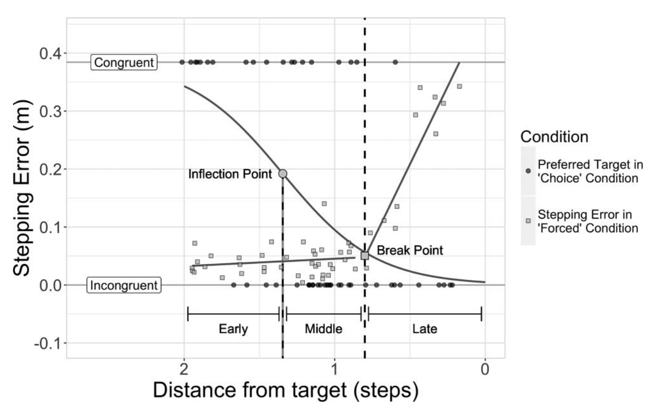

Figure 6. Depiction of procedure used to classify trials into early, middle, and late intervals. The figure shows the data and models from Figures 4a and 4b overlaid. The inflection point of the logistic regression denotes the boundary where this example subject's preferred target changed. The breakpoint of the segmented linear regression denotes where the subject's stepping accuracy began to degrade as a function of the distance at which the congruent target appeared. The inflection point defined the boundary between early and middle intervals and the break point defined the boundary between middle and late intervals.

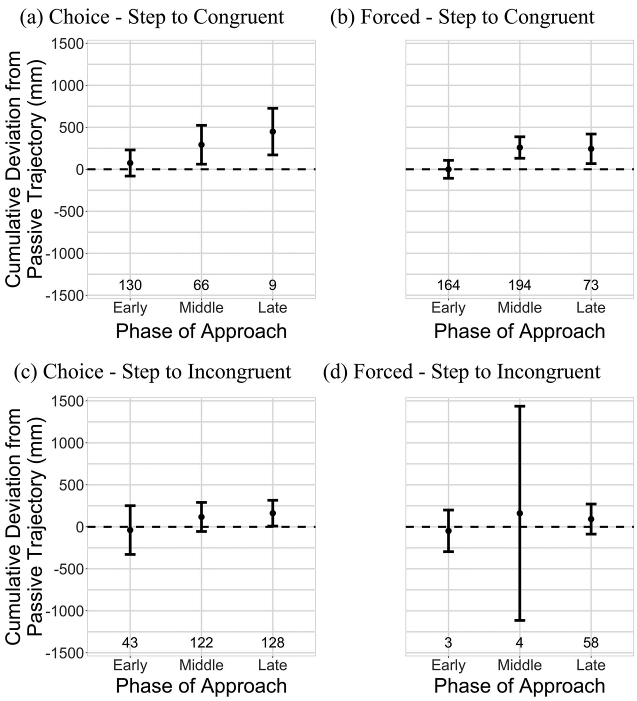

Figure 7. Mean deviations of the center of mass (COM) from the predicted passive trajectory of a three-dimensional (3D) pendulum with the same initial conditions. Deviations were centered relative to those observed in the control condition when only the congruent target was present (error bars are 95% confidence interval). A score of 0 indicates that COM movement was no different from this control condition, while positive values indicate COM movement deviated more from the passive trajectory than in the control condition. Along the *x*-axis, early, middle, and late refer to the interval in which the congruent target appeared, as explained in Figure 6. The values above each interval indicate the number of trials grouped into each bin. Columns represent Choice (a, c) and Forced (b, d) conditions, while rows indicate steps to congruent (a, b) and incongruent (c, d) targets.

foot placement selection (Moraes et al., 2007, 2004; Moraes & Patla, 2006). Walkers have been shown to prefer lengthening steps over shortening steps when required to make spontaneous adjustments to footholds away from a centrally located stepping target. Initially this seems surprising given that our findings reveal an increase in stepping error that results from lengthening a stride, especially relative to incongruent targets that require a shortened step. However, if we interpret this previous work as well as our findings with regards to a control strategy organized around moving as ballistically as possible, it seems plausible that when faced with only options to lengthen or shorten a step, walkers might trade a slight decrease (resulting from stride lengthening) in the ability to accurately place one's foot on a desired location for the minimization of interference with the ballistic forward momentum of the body.

In our study, the availability of a stepping target that was congruent with the rest of the path provided a stepping option that minimized the degree of interference with the ballistic trajectory of the body (relative to any option provided by an incongruent target). Congruent targets provided conditions for a step that were identical to both previous and future steps. Thus, stepping to the congruent target required only maintaining the ballistics of the body that were initialized during the preceding step, and left the body appropriately initialized for the upcoming step. Therefore, it is understandable that walkers would prefer congruent steps when the option was available before adjustments to the trajectory of the body needed to be made.

Switching (or Not) to a More Congruent Target Foothold

While the desire to move ballistically provides a strong motivation for preferring congruent targets over incongruent ones in general, it also means that walkers will prefer the incongruent target if it is the only one available when the dynamics of the step are being organized. In other words, if the congruent target appears after the body has already been directed toward the incongruent target, we would not expect walkers to step on the congruent target as this would require further modification of the ballistic trajectory of the step.

We found that if the congruent target appears later than 1.2 steps in advance, walkers are more likely to step onto the incongruent target than attempt to switch to the congruent target. Furthermore, across all subjects very few switches to the congruent target were made when it was not presented as an option until after the step to the incongruent target was initiated (mean % = 23.87; 95% CI = 4.51).

More important though, this is not because subjects were unable to accurately step on the congruent target if they did attempt to switch. Findings from the Forced block demonstrate that when subjects were forced to switch to the congruent target, they could do so without any significant increase in stepping error as long as the congruent target appeared no later than the early part of the affected step. Thus, if subjects preferred the congruent target whenever they were capable of stepping on that target without sacrificing accuracy, there is no compelling reason why they only made the switch when the congruent target appeared early on during the preceding step.

Instead, the tendency to prefer the incongruent target even when the congruent target appeared soon enough to be accurately stepped on can be readily understood in terms of a preference to exploit the dynamics of the body's structure by moving in a ballistic manner. Making appropriate adjustments to the initial conditions of a ballistic trajectory for an upcoming step requires using visual information during the preceding step to modify simple control variables of the ballistic trajectory, such as the direction and magnitude of the push-off force of the upcoming step (Matthis et al., 2015; Matthis & Fajen, 2013, 2014). If walkers select footholds based on a desire to move ballistically on each step, then once visual information has been used to tailor the initial conditions of the next step, changing foot placement based on new information (such as the appearance of the congruent target in this study) would require opposing the ballistic dynamics of the body. While this is not impossible, it appears to be the less desirable option during continuous, naturalistic locomotion.

For the same reasons that we would expect the congruent target to be more desirable if it is made available early on, the incongruent target becomes the more desirable of the two once the subject has passed the point at which the ballistic trajectory can be easily modified. After the end of the preceding step, the initial conditions for the ballistic trajectory on the upcoming step have been modified and passive dynamics have been organized to carry the walker to the incongruent target. Adjustments to foot placement after this point would require neuromuscular intervention that interferes with the prescribed ballistic trajectory.

Conclusion

Lee et al. (1982)'s classic study of elite long jumpers was the springboard for research on visual gait regulation. Over the next two decades, it became evident that much could be learned about the coupling of perception and action by studying how people walk and run over complex terrain. The picture of visual gait regulation that emerged from this research stands as one of clearest examples of how complex, adaptive behavior can emerge from the task-specific coupling of informational variables and parameters of the action system.

However, active perceptually guided control is not the only means by which to adapt gait to meet the demands of the terrain. Walkers can use a mixture of passive and active control that allows them to negotiate complex terrain while simultaneously exploiting the pendular structure of their body, which affords stability and energetic efficiency. This entails using visual information at strategic intervals during the gait cycle to modify the parameters that govern the passive dynamics of the body. Although walkers are capable of actively correcting the trajectory of the foot midflight if necessary to avoid an obstacle, there is a strong preference to not interfere with the ballistic movement of the body. Thus, we arrive at a refined view of visual gait regulation that captures how actors simultaneously exploit physical and informational constraints to achieve stable, efficient, and adaptive locomotion over complex terrain.

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