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Visual Control of Foot Placement When Walking Over Complex Terrain

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The aim of this study was to investigate the role of visual information in the control of walking over complex terrain with irregularly spaced obstacles. We developed an experimental paradigm to measure how far along the future path people need to see in order to maintain forward progress and avoid stepping on obstacles. Participants walked over an array of randomly distributed virtual obstacles that were projected onto the floor by an LCD projector while their movements were tracked by a full-body motion capture system. Walking behavior in a full-vision control condition was compared with behavior in a number of other visibility conditions in which obstacles did not appear until they fell within a window of visibility centered on the moving observer. Collisions with obstacles were more frequent and, for some participants, walking speed was slower when the visibility window constrained vision to less than two step lengths ahead. When window sizes were greater than two step lengths, the frequency of collisions and walking speed were weakly affected or unaffected. We conclude that visual information from at least two step lengths ahead is needed to guide foot placement when walking over complex terrain. When placed in the context of recent research on the biomechanics of walking, the findings suggest that two step lengths of visual information may be needed because it allows walkers to exploit the passive mechanical forces inherent to bipedal locomotion, thereby avoiding obstacles while maximizing energetic efficiency.

Keywords: locomotion, obstacle avoidance, visual control, dynamic walking model

When humans walk on flat, obstacle-free surfaces, many aspects of their behavior emerge naturally from the physical dynamics of the body. The steady-state gait cycle is dominated by an interchange between potential and kinetic energy shaped by the mechanical structure of bipedal walking, with vision playing little role in the placement of the feet. This understanding of gait was a driving force behind the development of passive–dynamic walking machines, which are unpowered robotic bipeds capable of walking unassisted and uncontrolled down shallow slopes (Collins, 2001; Kuo, 1999; McGeer, 1990). More recently, similar robots have been made to walk on flat ground by replacing the force supplied by gravity through the application of torque at the hip or by spring-loaded actuators in the feet, resulting in a remarkably human-like gait cycle (Collins, Ruina, Tedrake, & Wisse, 2005). Insights gained from these artificial walkers facilitated the development of the dynamic walking approach to the study of human gait, which explains how the remarkable efficiency of human walking derives from the ability to exploit the physical dynamics of the body in order to sustain locomotion with minimal actuation or control (Donelan, Kram, & Kuo, 2002; Kuo, 2007; Kuo & Donelan, 2010).

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The dynamic walking model offers a compelling account of the efficiency of steady-state gait over flat, obstacle-free terrain. However, many environments contain obstacles that must be avoided, irregularly spaced safe footholds (e.g., stepping stones), and surfaces that vary in traction, slant, and compliance. Accommodating such terrain involves detecting visual information about the layout of surfaces in the immediate foreground, and using such information to change stride length and width to land on safe footholds, increase ground clearance to step over obstacles, or change direction to circumvent environmental impediments. In other words, when such irregularities are encountered, locomotion by means of steady-state walking is not possible. Nonetheless, energetic efficiency is no less important when walking over extended regions of complex terrain. Therefore, the same principles that capture the efficiency of walking over flat terrain may also apply to walking over complex terrain.

The aim of the present study was to advance our understanding of the visual control of walking over complex terrain. We conducted two experiments designed to investigate how far ahead along the future path visual information is needed to maintain forward progress and avoid obstacles. We then place our findings within the context of the dynamic walking model, which provides a biomechanical basis for understanding how visual information is used to guide walking over complex terrain.

Visual Contributions During Walking Over Complex Terrain

Although it is possible to avoid an obstacle that is not identified until the very last moment (Patla, Prentice, Robinson, & Neufeld, 1991; Reynolds & Day, 2005), locomotion is likely to be far more stable and energetically efficient when movements are guided in an anticipatory manner. By identifying obstacles and safe footholds in advance, walkers can decide whether to step over an obstacle or walk around it and, when preferred footholds are unavailable, select alternative footholds that promote stability and forward progress (Moraes, Allard, & Patla, 2007; Moraes, Lewis, & Patla, 2004; Moraes & Patla, 2006). When two obstacles are present, anticipatory control allows walkers to step over the first obstacle in a way that facilitates stepping over the second (Krell & Patla, 2002). For humans and other animals, the visual modality is uniquely suited to identify potential obstacles and safe footholds at a distance (Patla, 1997). In this section, we discuss how visual information is used to guide locomotion over complex terrain, with a particular focus on the strategies that allow for anticipatory control.

Information-Based Strategies

One way in which locomotion can be guided in an anticipatory manner is by relying on prospective information in optic flow. By this account, locomotion is regulated by visual information in a continuous manner. The classic study of long jumping by Lee, Lishman, and Thomson (1982) provides an illustrative example of continuous control. Long jumping requires one to sprint down an approach path with the goal of placing the final step as close as possible to the edge of a track. Lee et al. found that variability in the toe-to-target distance increased throughout the early stages of the approach only to decrease dramatically in the final three steps preceding take off. The sharp decline in variability in the last three steps suggests that step length was actively regulated throughout the final approach to ensure landing on the takeoff board.

The relation between vision and locomotion in such tasks can be formalized by *laws of control* (Warren, 1988) that capture the coupling between some optical variable and some action variable. In the case of long jumping, a candidate action variable is vertical impulse, which can be modulated to increase or decrease stride length as necessary. Lee et al. (1982) showed that by coupling vertical impulse to the optically specified time to contact with the takeoff board, the flight times and stance times of the remaining strides sum to equal the time remaining before reaching the board. Thus, by this account, anticipatory control of stride length to ensure landing on the takeoff board is achieved by coupling an action variable and an optical variable.

This approach was later extended to describe how a runner might land on a series of irregularly spaced targets (Warren, Young, & Lee, 1986). However, subsequent research revealed that additional variables on both the information side and the action side might also be involved (Patla, 1989; Patla, Robinson, Samways, & Armstrong, 1989; but see Warren & Yaffe, 1989). Furthermore, there is evidence that the regulation of gait parameters such as stride length is achieved via a coupling to both visual and nonvisual sources of information (Berg & Mark, 2005; de Rugy, Montagne, Buekers, & Laurent, 2000), suggesting that the perceptual regulation of locomotion is more complex than is suggested by the aforementioned account (see Warren, 2007 for a discussion).

Using Visual Information in a Feed-Forward Manner

When people navigate cluttered environments, they often fixate obstacles or the ground near obstacles before stepping over them (Hayhoe, Gillam, Chajka, & Vecellio, 2009). Such fixations may be important, not only for gathering visual information about the obstacle, but also because generating a saccade may itself be used for visual guidance of the upcoming step (Hollands & Marple-Horvat, 2001). In many situations, however, people must shift their gazes away from the foreground to look at other objects, such as signs, scenery, or pedestrians who may be on a collision course (Rothkopf, Ballard, & Hayhoe, 2007). As might be expected given the multitude of subtasks that must be concurrently performed to guide locomotion, visual information from the foreground need not be continuously sampled. People can safely navigate moderately complex terrain by intermittently sampling obstacles and footholds that lie ahead (Mohagheghi, Moraes, & Patla, 2004; Patla, Adkin, Martin, Holden, & Prentice, 1996; Rietdyk & Drifmeyer, 2009). Even when there are no additional subtasks to draw attention away from the control of foot placement, gaze is not continually directed at the next target. Patla and Vickers (2003) reported that much of the time is spent making travel-gaze fixations (i.e., looking at a spot that moves forward with the person) or fixating positions that are two or more step lengths ahead (see also, Fowler & Sherk, 2003; Wilkinson & Sherk, 2005).[1] Likewise, when people navigate a room densely cluttered with furniture and other obstacles, they rarely fixate these objects prior to stepping over them (Franchak & Adolph, 2010). Taken together, these findings suggest that people may fixate obstacles prior to crossing them but that they can rely on peripheral vision if the task demands fixation of other objects in the environment. Indeed, when a planar object was unexpectedly dropped on a treadmill, participants stepped over it successfully on the basis of peripheral vision. Even when gaze was unconstrained, participants rarely fixated the unexpected obstacle before stepping over it (Marigold, Weerdesteyn, Patla, & Duysens, 2007).

In addition to relying on peripheral vision, walkers may also use visual information in a feed-forward manner. Evidence of feed-forward control is provided by the finding that people can step over a single obstacle up to five steps away without any visual information with a success rate of ~90%, provided that they were walking when vision was occluded and that walking is uninterrupted after occlusion (Patla, 1998; Patla & Greig, 2006). Similarly, if a cat's vision is occluded as it walks down a cluttered hallway, it will still make on average two to four accurate steps before colliding with an obstacle (Wilkinson & Sherk, 2005). Some insight into the neural bases of feed-forward control can be gleaned from studies of cat locomotion which reported increased activity in Area 5 of the posterior parietal cortex in the steps preceding a step over an obstacle. Although some cells were correlated with the movement of the contralateral limb, other cells change to reflect the activity of the first limb to pass over the obstacle, regardless of whether that is the contralateral or ipsilateral limb. These findings suggest that cells in this area play a

[1] More recently, questions have been raised about the prevalence of travel-gaze fixations (Land & Tatler, 2009; Pelz, Purington, & Herbert, 2009). Both studies question the claim that gaze smoothly drifts forward with the observer and suggest that, instead, the behavior is better characterized as smooth downward movement to maintain fixation on a feature in the environment with intervening upward saccades. Furthermore, gaze behavior in naturalistic environments is found to be variable (Turano, Geruschat, Baker, Stahl, & Shapiro, 2001), casting further doubt on the prevalence of travel gaze in visually guided locomotion.

functional role in the planning and execution of anticipatory changes in gait (Andujar, Lajoie, & Drew, 2010; see McVea & Pearson, 2009 for a review).

Summary

A few main points are clear from the existing research on the visual control of locomotion. First, visual information is generally used in a feed-forward manner without continuous sampling to negotiate obstacles several steps ahead. Second, people may fixate obstacles approximately two steps prior to crossing them but more often rely on peripheral vision, especially in more complex environments. Third, when the task demands a high degree of spatiotemporal precision (as in long jumping), gait parameters such as stride length can be continuously regulated based on visual information to ensure accurate foot placement.

Aims of the Present Study

Although it is clear that locomotion is controlled in an anticipatory manner, the majority of research on this topic has focused on situations in which walkers must negotiate one or at most two foot targets or obstacles. Considerably less is known about how visual information is used to control gait when walking over longer stretches of complex terrain with irregularly spaced obstacles and safe footholds. In this study, we investigated how far along the future path visual information is needed to successfully control walking over complex terrain. This is an important question because if visual information from more than one step ahead is needed, then the visual control strategy for walking over complex terrain must explain how footholds for the next step are chosen in a way that allows the walker to better negotiate more distant obstacles. At normal walking speeds, people are capable of stepping over solitary obstacles that are not detected until they lay within a single step (Patla, Prentice et al., 1991). As such, one might expect that visual information from a single step ahead may be sufficient to maintain forward progress and avoid stepping on obstacles. On the other hand, in complex environments containing many obstacles, relying on visual information from more than one step ahead may allow people to step over nearby obstacles in a way that that leaves them in a better position to negotiate distant obstacles. In this regard, control strategies that use visual information from several steps ahead could promote accuracy, stability, and energetic efficiency.

Experiment 1

For this study, we developed an experimental paradigm to measure the minimum distance along the future path that an individual must see to control foot placement when walking over complex terrain. Participants walked from a home position to a goal while attempting to avoid stepping on an array of virtual obstacles that were strewn across the path. In the full-vision condition, the entire field of obstacles was visible for the duration of each trial. In the other conditions, obstacles were visible only when they were located within a window of visibility centered on the subject's head as he or she moved through the room (see Land & Horwood, 1995; Patla, 1997; Warren, 1988; Wilkie, Wann, & Allison, 2008; Zhao & Warren, 2012 for other studies that have used a visibility-window manipulation to investigate the use of visual information to guide locomotion). When the visibility of obstacles was constrained, participants had to walk over the field of obstacles with limited visual look-ahead of the upcoming path. By examining the way that walking performance degrades as a function of the size of the visibility window, we can measure how far along the future path visual information is needed to maintain normal walking performance. When the visibility window is too small, such that visual information that is needed to control walking is unavailable, participants should be more likely to step on obstacles. As the visibility window increases, the frequency of collisions should decrease. Eventually, we expect to reach a point of diminishing returns, beyond which walking is indistinguishable from the full-vision condition.

Method

Participants. Participants in Experiment 1 included nine men and one woman ($N = 10$; mean age = 19.1 years, $SD = 0.6$; mean height = 1.80 M, $SD = 0.1$; mean weight = 77.9 kg, $SD = 13.4$). Participants were recruited from psychology courses and received extra credit for participating. All participants reported no motor impairments and normal or corrected-to-normal vision. The protocol was approved by the Institutional Review Board at Rensselaer Polytechnic Institute and all participants gave informed consent before performing the experiment.

Equipment. The experiment was conducted using a 14-camera Vicon motion-capture system running Vicon IQ 2.5 software. The motion capture system tracked the positions of 45 retroreflective markers that were attached to tight-fitting, elastic shirt and leggings worn by participants. The markers were placed in accordance with a full-body biomechanical template. Participants completed the experiment barefoot in order to avoid any irregularities caused by differences in footwear.

A Sanyo PLC-XP45 projector was used to display virtual obstacles onto the floor at a resolution of 1024×768 with a brightness of 3500 ANSI lumens. The projector was located 1.75 m behind the end position at a height of 1.15 m pointed at the ground at a relatively low angle of incidence (~20 degrees). The projector's range covered a trapezoid that was roughly 1.05 m at the end position nearest the projector and 2.40 m near the starting position, 3.60 m away (Figure 1A).

A field of 15 cm $\times$ 15 cm blue square obstacles spanned the entire trapezoidal area covered by the projector. There were 10 different configurations of obstacles, each consisting of pseudo-random arrangements of 40 obstacles. Obstacle arrays were chosen to be dense enough that participants would have to make gait modifications to avoid stepping on the obstacles, but sufficiently sparse that participants could follow a straight path from the start position to the end position. The computer that displayed the virtual obstacles received input from the motion capture system, so that if a subject stepped on a virtual obstacle, it would register a collision, play a sound, and change color from blue to bright green.

The motion-capture and projector systems were integrated using custom software. The projector position was calibrated using a method based on the Tsai calibration algorithm (Tsai, 1987). Calibration points defined in pixel (i.e., computer screen) coordinates were displayed on the lab floor by the projector. A marker tracked by the motion-capture system was placed on each calibra-

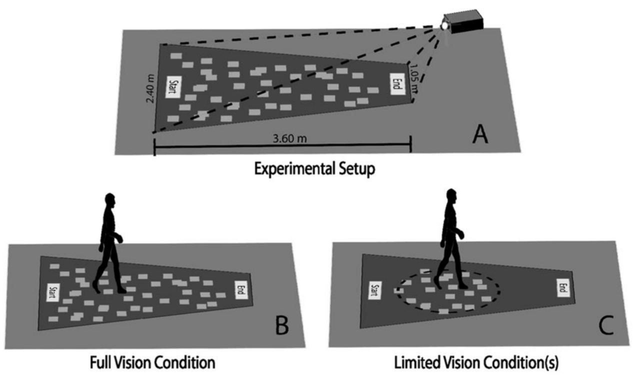

Figure 1. The experimental set up used in Experiments 1 and 2. An LCD projector displayed a field of virtual obstacles on the ground (A). In the full-vision control condition (B), the entire field of obstacles was visible throughout the trial. In the limited vision conditions (C), obstacles were only visible when they were within a certain visibility distance of the subject's position.

tion point. The position of the marker in world coordinates and the position of the corresponding calibration point in screen coordinates were fed into an algorithm that calculated the transformation between screen coordinates and world coordinates. Upon completion of this calibration process, the location of the subject (defined as the mean of the positions of the four markers encircling the subject's head) could be compared with the location of virtual obstacles projected onto the floor, which allowed us to draw the visibility window in a location centered on the subject's head. Similarly, the locations of markers on the subject's feet could be compared with the locations of virtual obstacles, which allowed us to detect collisions.

Task and procedure. Participants began the experiment by completing 10 free-walking trials, in which there were no obstacles and participants were asked to walk at a brisk pace from a start position (marked with tape on a carpeted floor) to an end position 3.6 m away. Data from these trials were used to normalize measures recorded in the other conditions.

Following the free-walking trials, participants walked across the field of obstacles at the same speed that they did in the free walking condition while attempting to avoid stepping on any of the virtual obstacles. They were also instructed to walk in a straight line between the start and end positions, stepping over obstacles as necessary rather than steering around them. Lastly, participants were told not to tip-toe around obstacles, but to place each foot fully on the ground with each step.

Although participants were instructed to walk quickly without stepping on the obstacles, there was no mechanism in place to enforce walking speed or stepping accuracy. We chose not to impose strict guidelines on walking speed or accuracy because we felt that it was important to know how participants would adapt to changes in visibility without unnatural constraints on their behavior.

Design. Each experimental session comprised two identical blocks of 70 trials, for a total of 140 trials per subject. The first 10 trials of each block were in the free walking condition. The next 10 trials were in the full-vision control condition, in which virtual obstacles were present and the full array of obstacles was visible throughout the entire trial (Figure 1B). The remaining 50 trials were limited vision trials in which obstacles were visible only when they fell within the visibility window—that is, when they were within a certain distance of the vertical projection of the subject's head on the floor (Figure 1C). We chose to manipulate visibility-window size as a blocked rather than randomized variable in an effort to reveal the best possible performance in each condition. Had we randomized visibility-window size, performance may have been worse because participants might have had difficulty rapidly adapting their behavior to trial-by-trial changes in the size of the visibility window.

The radius of the visibility window = 1, 2, 3, 4, or 5 step lengths. At normal walking speeds, preferred step length is roughly 70% of leg length (Kuo, 2007)[2]. As such, the size of the five windows (W) were defined as follows: $W = 0.7kL$, where k is an integer between 1 and 5, and L is the subject's leg length, taken as the vertical height of the right thigh marker located at the greater trochanter of the femur. Thus, in the smallest window ($k = 1$), participants were only able to see obstacles that were within roughly one step length ($0.7L$) of their current position and in the largest window ($k = 5$), obstacles were visible within roughly five step lengths ($3.5L$).

As participants walked through the field of obstacles, the leading edge of the visibility window eventually reached the end position. From that point until the end of the trial, the size of the visibility window was effectively equal to the distance from the subject to the end position. This means that the difference in window sizes across conditions grew smaller toward the end of each trial. For example, when the subject was within one step length of the end position, the window sizes were the same in all five conditions. When the subject was within two step lengths of the end position, the window sizes were the same in conditions with $k \geq 2$. This may have reduced the overall effect of the visibility-window manipulation. However, even for the larger window sizes, the first few steps of each trial were unaffected by this limitation. Thus, if there are differences in behavior across visibility-window sizes, then these differences should still be reflected in the dependent measures.

Limited-vision trials were presented in subblocks of 10 trials, with window size constant within each subblock. The order of window sizes varied randomly across participants, with the exception that sequences were discarded if the first condition was either the smallest ($k = 1$) or the largest ($k = 5$) visibility window. This was to ensure that participants were comfortable with the task before encountering one of the two extremes in the range of visibility-window sizes.

To summarize, each block comprised 70 trials presented in the following order: 10 free-walking trials, 10 full-vision trials, and five subblocks of 10 limited-vision trials. Participants completed one block of 70 trials, had a short break, and then completed a second block with the same design, order of subblocks, and num-

[2] Estimating participants' step length as 70% of leg length was intended to be a rough approximation used to ensure that the visibility windows were scaled to each subject's body dimensions. However, post hoc comparison between participants average step length and their leg length reveals that subject mean step length was very close to our estimate. Mean step length for all participants in Experiment 1 in the obstacle-free condition was 0.68L ($SD = 0.06$).

ber of trials. Each complete session included 140 trials, yielding 20 repetitions for each of the seven conditions.

Analyses. The primary dependent measure in this experiment was the average number of collisions per trial. Although participants were instructed to walk at the same speed that they walked during the free-walking condition, there was no mechanism in place to enforce this guideline. As such, we expected that some participants might walk more slowly in the smaller window conditions, effectively sacrificing walking speed to maintain stepping accuracy. Therefore, mean walking speed was also recorded as a secondary measure of walking performance. Mean walking speed was calculated for each trial by dividing the distance from the start position to the end position by the amount of time it took to walk that distance. To account for between-participants differences in body dimensions, mean walking speed in each visibility condition was normalized to mean walking speed in the free-walking condition. That is, each subject's walking speed in each condition was divided by his or her mean walking speed in the free walking condition. As such, the reported values correspond to the percentage of normal speed at which participants walked.

Ideally, the analyses would have also included a measure of dynamic stability, as it is conceivable that participants could maintain walking speed and avoid collisions by taking less stable steps. Unfortunately, the only presently available method for quantifying stability during walking, the margin-of-stability (MOS) measure (Hof, Gazendam, & Sinke, 2005) is not appropriate for this task. The MOS offsets the vertical projection of the center of mass (COM) by its momentum, and then measures the distance of the extrapolated COM from the limits of the base of support at each step.

The key assumption underlying the use of the MOS as a measure of stability is that a large MOS reflects a stable step, a small MOS reflects a less stable step, and a negative MOS (indicating that the extrapolated COM is outside the bounds of the base of support) reflects an unstable step. This assumption makes sense with respect to static postures (e.g., standing), for which stability is defined by the structural relationship between the COM and the base of support; that is, stability is guaranteed as long as the COM (or extrapolated COM) stays within the bounds of the base of support. During walking, however, stability is not defined solely by the position of the feet relative to the body. Dynamic stability during gait involves adaptive movements of the body relative to its current state and the state of the environment. As such, the relation between the MOS of a step and dynamic stability is more complex during walking, especially in complex environments such as those used in this study, in which symmetric stepping behavior is not possible.

Results and Discussion

The results of Experiment 1 are presented in Figure 2. Individual univariate repeated-measures ANOVAs were conducted on each of the dependent variables. An application of Mauchy's test revealed that the sphericity assumption had been violated for both variables, so a Huynh-Feldt correction was applied to these results. The two univariate repeated-measures ANOVAs revealed a significant effect of visibility window on number of collisions, $F(1.66, 14.70) = 26.12$, $p < .01$, partial $\eta^2 = .74$, and mean walking speed $F(1.62, 14.55) = 9.91$, $p < .01$, partial $\eta^2 = .52$.

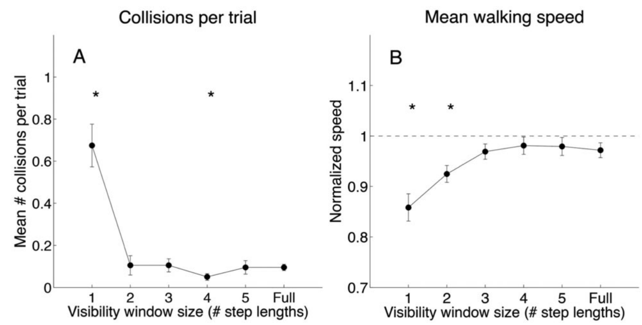

Figure 2. Mean number of collisions per trial (A) and mean normalized walking speed (B) in each visibility condition for all participants in Experiment 1. Step length was estimated at 0.7 × leg length. Walking speed for each subject was normalized by the subject's average walking speed in the free walking condition (M = 0.98 m/s). Error bars represent ± 1 *SEM.* Asterisks denote conditions that are significantly different from the full-vision control condition ($p < .05$).

Planned comparisons (at the $p < .05$ level) were performed to compare results for each visibility window with the full-vision control condition. The smallest window-size condition ($k = 1$) was the only condition in which the mean number of collisions significantly exceeded the mean number of collisions in the control condition. For reasons that we cannot explain, there was also a small but statistically significant decrease in number of collisions when the size of the window was four steps. Walking speed was significantly slower in the two smallest window-size conditions than in the control condition.

The results of Experiment 1 revealed that walking performance (measured in terms of number of collisions and walking speed) was significantly affected when vision was limited to less than two step lengths ahead. When participants were able to see two step lengths ahead, collisions were no more frequent than they were in the full-vision condition. However, participants did walk more slowly in this condition, suggesting that walking performance was still affected when participants could see two step lengths ahead. When participants could see three or more step lengths ahead, they were able to perform the task as well as they did in the full-vision condition. Taken together, the results of Experiment 1 indicate that walking performance returned to near-baseline levels when participants could see two to three step lengths ahead.

Different strategies for adapting to small-visibility windows. Participants were instructed to avoid stepping on obstacles while walking at the same speed as they did in the free-walking condition. However, because we did not want to overly constrain behavior in this experiment, participants were not told which of these two edicts was more important. Not surprisingly, participants differed in the degree to which they followed each guideline. To examine these differences, we split participants into two groups based on whether their normalized walking speed was greater than 0.95 across all conditions (see Figure 3). Two of the 10 participants satisfied this criterion, with the remaining eight participants walking more slowly in the smaller window-size conditions. As one would expect, the two participants who maintained a consistent walking speed were more likely to step on obstacles than those who slowed down as window size decreased. However, except for the smallest window-size condition, the differences between

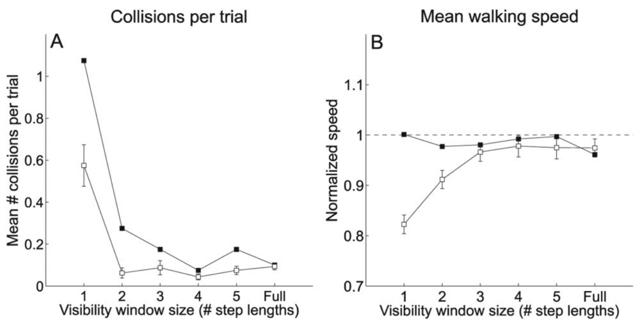

Figure 3. Mean number of collisions per trial (A) and mean normalized walking speed (B) for participants who maintained a consistent walking speed in all window-size conditions (filled squares) and participants who did not (open squares) in Experiment 1. Error bars represent ± 1 s.e.m. No error bars are provided for the filled squares because there were only two participants in that group.

groups were small. Moreover, when vision was restricted to two steps ahead, there was only a small increase in the number of collisions for participants who maintained a consistent walking speed across all conditions. This analysis provides further support for the claim that visual information from two step lengths is sufficient to maintain forward progress and avoid stepping on obstacles.

Experiment 2

In Experiment 1, we observed large differences between the two smallest window sizes, smaller differences between the second and third window sizes, and no differences as window size increased beyond three step lengths. Experiment 2 was designed to explore this effect in more detail by testing a narrower range of visibility-window sizes centered around the two step-length distance.

Method

Participants. Participants in Experiment 2 were seven men and five women ($N = 12$; mean age = 19.1 years, $SD = 1.2$; mean height = 1.70 m, $SD = 0.1$; mean weight = 66.5 kg, $SD = 9.5$); were recruited from psychology courses; and received extra credit for participating. All participants reported no motor impairments and normal or corrected-to-normal vision, and none had participated in Experiment 1.

Equipment, task, and data analysis. Experiment 2 was identical to Experiment 1 with the following exception. Whereas the five visibility windows used in Experiment 1 corresponded to distances of one to five step lengths in increments of one step length, in Experiment 2 the five visibility windows corresponded to distances of 1–3 step lengths in increments of 0.5 step lengths. That is, on limited vision trials, obstacles were visible when they fell within 1.0, 1.5, 2.0, 2.5, or 3.0 step lengths of the subject's position.

Results and Discussion

As in Experiment 1, the data from Experiment 2 were analyzed using univariate repeated-measures ANOVAs for both dependent variables. The results from Experiment 2 are presented in Figure 4. Mauchy's test revealed that the sphericity assumption was violated for both dependent measures, so a Huynh-Feldt correction was used. Univariate tests revealed a significant effect of visibility-window size on number of collisions, $F(2.64, 29.01) = 70.71$, $p < .01$, partial $\eta^2 = .87$, and on mean walking speed, $F(2.20, 24.25) = 8.65$, $p < .01$, partial $\eta^2 = .44$. Planned comparisons were used to compare performance in each visibility window against the full-vision condition. Significant differences (at the $p < .05$ level) were found in the number of collisions for window sizes 1.0, 1.5, 2.0, and 2.5 compared with the full-vision control condition. For mean walking speed, significant differences were found for all five visibility-window sizes compared with the control condition.

The results of Experiment 2 are largely consistent with those of Experiment 1, with a few exceptions. First, there was a small but significant increase (relative to the full-vision condition) in the number of collisions when visibility-window size was 2.0 and 2.5 step lengths, whereas no such increase was observed in the equivalent conditions in Experiment 1. Second, there was a small but significant decrease in mean walking speed when the visibility window was three step lengths, though no such difference was found in the corresponding condition in Experiment 1. These differences may reflect a range effect introduced by the different set of visibility-window sizes used in Experiment 2. Nonetheless, in both experiments, collisions were most frequent and walking speed was slowest when vision was constrained to fewer than two step lengths ahead.

As in Experiment 1, we separated participants into two groups based on whether their normalized walking speed was greater than 0.95 across all conditions (see Figure 5). For the four participants who satisfied this criterion, the mean number of collisions in window sizes 1.0, 2.0, and 3.0 was similar to that in Experiment 1 (compare filled squares in Figures 3 and 5). The similarity across experiments is also apparent for participants who slowed down in the smaller window-size conditions (compared open squares in Figures 3 and 5). Thus, both groups of participants performed similarly to their corresponding groups in Experiment 1.

More important, Experiment 2 provides a finer grained look at the effect of varying the size of the visibility window. Experiment 1 demonstrated that performance was poor with visual information

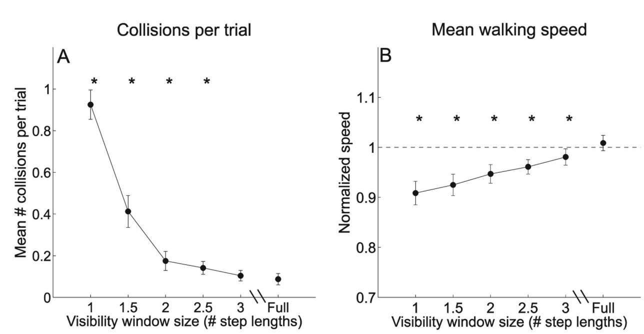

Figure 4. Mean number of collisions per trial (A) and mean walking speed (B) in each visibility condition for all participants in Experiment 2. Note that unlike Experiment 1, there is a discontinuity between the largest visibility window (3 step lengths) and the full-vision condition (roughly 6 step lengths). Asterisks denote a significant difference from the control condition ($p < .05$).

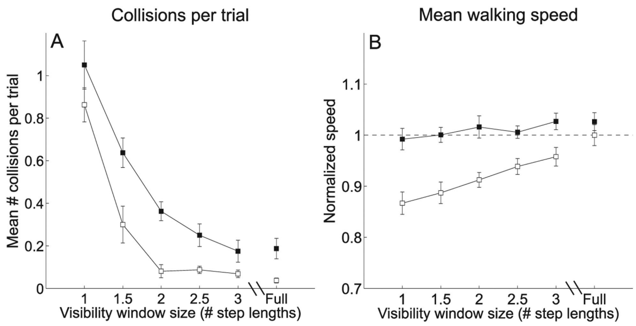

Figure 5. Mean number of collisions per trial (A) and mean normalized walking speed (B) for participants who maintained a consistent walking speed in all window-size conditions (filled squares) and participants who did not (open squares) in Experiment 2. Error bars represent ± 1 s.e.m.

from only one step length ahead and near baseline with visual information from two step lengths ahead. In Experiment 2, the number of collisions was considerably higher in the 1.5 step-length window-size condition than in the two step-length window-size condition. This was true for participants who maintained a consistent walking speed across conditions and for those who slowed down in smaller window-size conditions. Thus, the results suggest that when visual information from at least two steps ahead is available, people can avoid stepping on obstacles with little or no decrease in walking speed. When visual information is restricted to one or 1.5 step lengths, people are unable to consistently avoid obstacles or maintain a normal walking speed.

General Discussion

We presented the results of two experiments designed to measure how far along the future path people need to see to successfully walk over terrain with densely packed obstacles. The largest degradation in walking performance was found when visual information about upcoming obstacles was limited to less than two step lengths ahead. Beyond this distance, walking performance showed only minor deviations from baseline performance, which disappeared when vision was extended to 2.5 to three step lengths. This suggests that when walking over complex terrain, visual information from two to three steps ahead is needed to maintain forward progress and avoid obstacles.

Our results offer a possible explanation for the findings of previous studies demonstrating that gaze is normally directed two step lengths ahead (Fowler & Sherk, 2003; Marigold & Patla, 2007; Patla & Vickers, 2003). If visual information from beyond two steps ahead is not needed to guide foot placement, then a reasonable strategy would be to direct gaze two steps ahead and rely on peripheral vision to sample information from within two step lengths, occasionally shifting gaze upward to serve other locomotor tasks (e.g., avoid moving obstacles, navigate to distant landmarks).

In the remainder of the General Discussion, we offer a possible explanation for why the guidance of foot placement is impaired when visual information from less than two steps ahead is unavailable. Our explanation draws upon the dynamic walking approach to the study of human gait, which we briefly mentioned in the introduction and now describe in more detail.

The Dynamic Walking Approach and the Two-Step Visibility Distance

During the single-support phase of gait, when one leg is planted and the other leg is swinging forward, the human body is mechanically similar to an inverted pendulum (Cavagna & Margaria, 1966; Usherwood, Szymanek, & Daley, 2008; Winter, 1995). The individual's COM serves as the bob of the pendulum and is supported over the pivot point at the ankle joint by the stance leg, which remains relatively stiff during the single-support phase (Kuo, 2007). The passive trajectory of the COM (i.e., the trajectory that the COM would follow in the absence of muscular intervention) depends on two factors: (a) the location of the planted foot, which defines the base of the inverted pendulum, and (b) the position and velocity of the COM at the beginning of the single-support phase (i.e., the initial conditions of the inverted pendulum). Because these two determinants are fixed before the onset of the single-support phase, the passive trajectory of the COM is completely determined at toe off. Furthermore, the range of possible landing locations for the swing foot is tightly constrained by the trajectory of the COM.

When walking over flat, obstacle-free terrain, foot placement is primarily determined by the movement of the COM and the lower limbs, with sensory control mostly relegated to the maintenance of stability in the medial-lateral dimension (Bauby & Kuo, 2000; O'Connor & Kuo, 2009). When obstacles are present, however, following the passive trajectory of the COM may leave the walker in a position wherein no safe footholds are available. In such situations, the trajectory may be adjusted midflight by applying muscular torque to the lower limbs or upper torso, or by swinging the arms. However, such movements require metabolic energy and are thereby energetically costly. Although it might occasionally be necessary to apply muscular forces midflight (e.g., to recover from a slip, or to avoid an obstacle that is detected at the very last moment), this is not an effective strategy for traveling long distances, where energetic efficiency is paramount. This consideration explains why locomotion is so impaired when visual information about the upcoming path is constrained to only one step length ahead, as it was in the one-step-length condition in Experiments 1 and 2. As illustrated in Figure 6 (see dark gray skeletons), by the time that the relevant visual information became available in the one-step-length condition, the walker was already in the single-support phase. Because the passive trajectory of the COM was determined earlier (at toe off), the walker would have needed to resort to inefficient midflight adjustments to avoid stepping on unexpected obstacles.

Next, let us consider why walking performance improves as visual information from further ahead becomes available. The initial velocity of the COM is largely determined by the push-off force that begins just before the double-support phase (Kuo & Donelan, 2010). In steady-state walking, the push-off force restores the mechanical energy that is lost during the step-to-step transition, but in complex terrain it may also be used to tailor the trajectory of the COM to facilitate landing on a safe foothold at the end of the single-support phase. If visual information about the layout of obstacles is available before the beginning of the single-support phase, the walker may be able to redirect the COM toward available footholds by applying an appropriately scaled push-off force. In the present study, visual

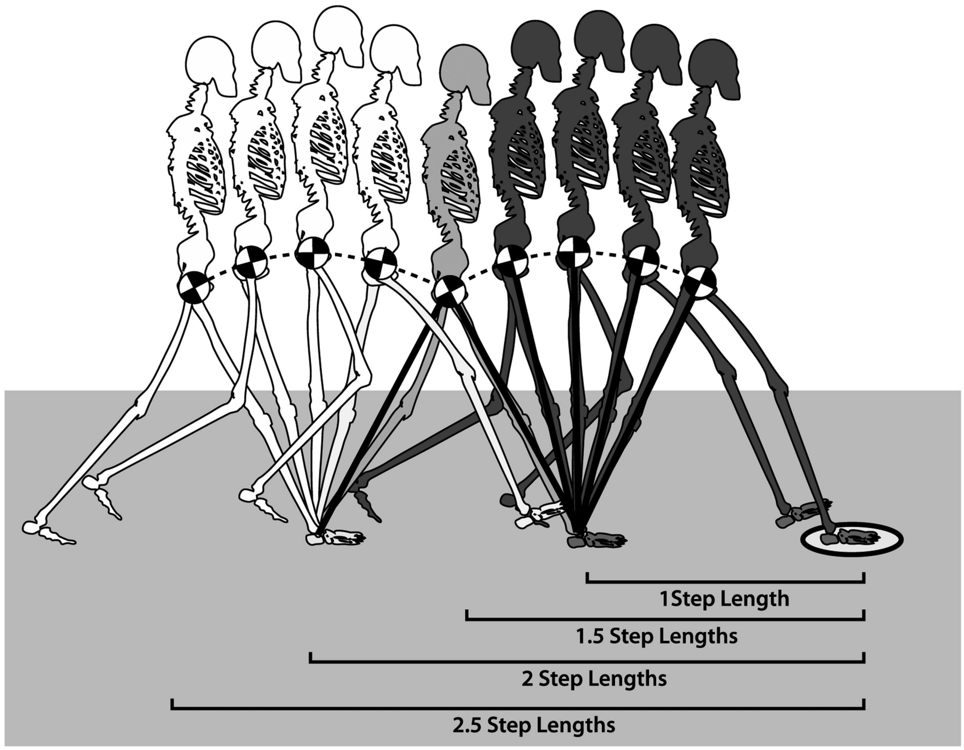

Figure 6. Diagram illustrating the location and configuration of a walker when visual information about a target foothold became available in the 1.0, 1.5, 2.0, and 2.5 step length conditions. Dark gray skeletons indicate locations of walker during single-support phase of the last step before the target. Light gray skeleton indicates location during the previous double support phase. White skeletons indicate locations before the double support phase. From "Humans exploit the biomechanics of bipedal gait during visually guided walking over complex terrain" by J. S. Matthis and B. R. Fajen (in press), *Proceedings of the Royal Society B*.

information was available before the beginning of the single-support phase when the visibility window was at least 1.5 step lengths (Figure 6, light gray skeleton). Thus, by this account, walking performance may have improved when the size of the visibility window increased from one to 1.5 step lengths because participants could use visual information to adjust the push-off force in the step-to-step transition to guide the COM toward safe footholds.

The other determinant of the passive trajectory of the COM is the location of the planted foot. Like the initial position and velocity of the COM, the location of the planted foot can also be adjusted to facilitate obstacle avoidance in an upcoming step. However, because the location of the planted foot is fixed upon contact with the ground, visual information from two full step lengths ahead is needed to adjust this parameter in response to upcoming terrain (Figure 6, white skeletons). Thus, when the visibility window constrained vision to 1.5 step lengths, walkers can use visual information to regulate only one of the two determinants of the passive trajectory of the COM (i.e., the initial velocity of the COM). When visual information is available from two full step lengths ahead, the second determinant (the location of the planted foot) can also be modulated by visual information about the layout of obstacles. This could account for the improvement in walking performance as the size of the visibility window increased to two step lengths and greater.

If visual information from two step lengths ahead is sufficient to control both determinants of the passive trajectory of the COM, then why did we observe weak effects of the visibility window beyond two step lengths? One possible explanation is that humans are not capable of instantaneously using visual information to modulate action. When visual information from two step lengths ahead was available, the layout of obstacles in the vicinity of a given step S_t was visible shortly before heel strike on the previous step S_{t-1}. However, because that information cannot be instantaneously used, it may be too late to select an appropriate foothold for step S_{t-1}. This could explain why participants walked slightly more slowly in the 2.5-step-length condition.

Another possible explanation for the weak effects of visibility-window size beyond two step lengths is that individual steps are not independent actions. Each step depends on previous steps just as it defines the preconditions for upcoming steps. As such, individual steps are discrete events that are highly interdependent and nested within the longer time scale of a continuous gait cycle. Although visual information from two step lengths ahead is sufficient to control both determinants of the passive trajectory of the COM for a single step, being able to see beyond two step lengths may allow walkers to better exploit passive forces when foot placement is constrained over a series of steps. This may explain why we observed small effects of visibility-window size beyond two step lengths.

Future Directions

Future research should explore the robustness of these findings across variations in terrain and walking speed. We would expect an increase in obstacle density to result in an overall increase in the frequency of collisions and an overall decrease in walking speed. However, if footholds are chosen to allow walkers to maximally exploit passive forces, then visual information from two step lengths ahead should be sufficient regardless of obstacle density.

Predicting the effects of variations in walking speed is more complicated. If walkers move slowly enough, they may be able to reliably avoid obstacles even if they can only see one step length ahead. Therefore, the finding that less than two step lengths of visual information is insufficient may not generalize to slower walking speeds. When moving at faster-than-normal walking speeds, additional factors such as perceptual-motor processing limits and having to overcome strong inertial forces of the legs during the swing phase may limit one's ability to redirect the COM in a single step. Under such conditions, the ability to make use of visual information sooner than two steps ahead may allow walkers to better negotiate complex terrain at fast walking speeds.

Conclusion

In the present study, we used a novel experimental paradigm to investigate how far along the future path people need to see to guide foot placement when walking over complex terrain. We found that when visibility is constrained to fewer than two steps, walkers decrease walking speed and have more difficulty avoiding obstacles. When visual information from two or more steps ahead was available, walking performance was comparable to performance when vision was unconstrained. Thus, visual information from at least two steps ahead is needed to guide foot placement when walking over complex terrain. Drawing upon recent research on the biomechanics of walking, we propose that when walkers have visual information from at least two step lengths ahead, they can fully exploit passive mechanical forces to steer the COM in a way that allows them to land on safe footholds.

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