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Humans exploit the biomechanics of bipedal gait during visually guided walking over complex terrain

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How do humans achieve such remarkable energetic efficiency when walking over complex terrain such as a rocky trail? Recent research in biomechanics suggests that the efficiency of human walking over flat, obstacle-free terrain derives from the ability to exploit the physical dynamics of our bodies. In this study, we investigated whether this principle also applies to visually guided walking over complex terrain. We found that when humans can see the immediate foreground as little as two step lengths ahead, they are able to choose footholds that allow them to exploit their biomechanical structure as efficiently as they can with unlimited visual information. We conclude that when humans walk over complex terrain, they use visual information from two step lengths ahead to choose footholds that allow them to approximate the energetic efficiency of walking in flat, obstacle-free environments.

1. Introduction

In order to complete a complicated floor routine, gymnasts harness the rotational and translational inertia of their bodies to perform spectacular motions that would be impossible on the basis of muscle activation alone. A gymnast's understanding of the physics of the human body need not be conscious. The human motor system has an impressive ability to use the passive mechanical forces inherent to a moving body in order to perform a wide variety of complex actions. Even something as simple as a cartwheel requires the exploitation of the rotational inertia of the lower limbs to swing the body over the wrists in a way that could never be accomplished by muscle activation alone [1].

Although walking may not be as dramatic as gymnastics or cartwheels, humans also exploit the forces inherent to bipedal walking in the maintenance of a steady-state gait [2,3]. Rather than struggling against the inertial forces generated during walking, the locomotor system harnesses and redirects these passive mechanical forces in order to generate a stable and efficient walking gait. This approach to the study of locomotion has its origins in research on passive dynamic walking robots. These simple, mechanical bipedal robots capitalize on the physical dynamics of bipedal gait in order to walk with no actuation down a shallow slope [4–7]. Minimal actuation in the form of foot-springs or hip actuators allows these robots to walk over flat ground with an energetic cost of transport that is comparable with a human and is an order of magnitude less than the cost of transport of traditional walking robots [8]. Insights gained from passive dynamic walking robots explain the energetic efficiency of human walking in flat, obstacle-free environments [9], but efficiency is no less important when walking over complex terrain such as a rocky trail. In this study, we investigated whether the principles underlying the efficiency of human walking in flat, obstacle-free environments provide insights into the visual control of foot placement when walking over complex terrain.

The visual information that is used to control foot placement has been extensively studied, beginning with Lee *et al.*'s [10] classic study showing that long jumpers regulate step length based on visual information about the time to

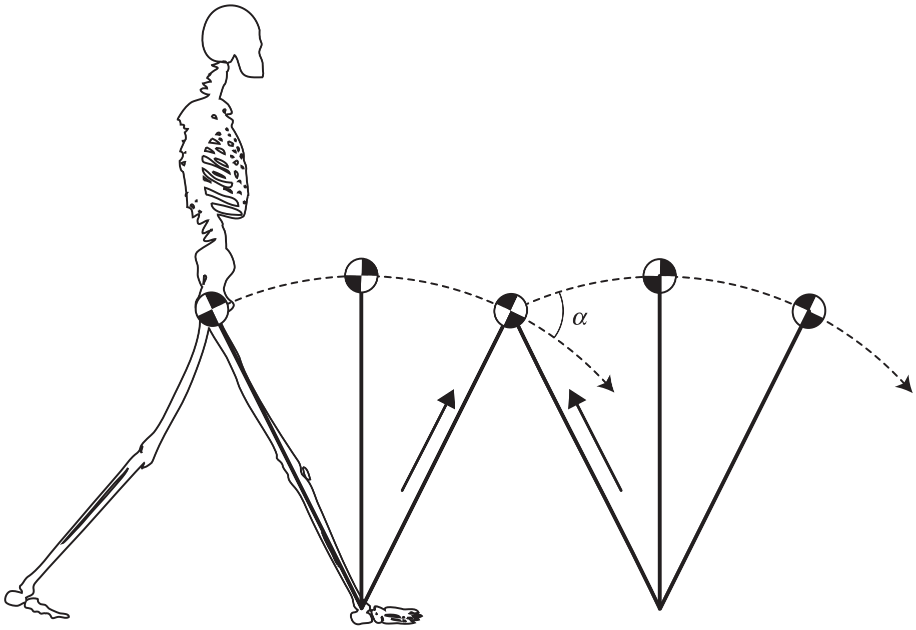

Figure 1. A conceptual diagram summarizing the dynamic walking perspective. The walker's COM follows a ballistic, passive trajectory during the single-support phase governed by the dynamics of an inverted pendulum. During the double-support phase, or step-to-step transition, the positive work of the trailing leg and the negative work of the leading leg (upward pointing arrows) redirect the COM's trajectory from a downward arc to the upward arc necessary for the next step. The energetic cost of this redirection of the COM is proportional to α.

contact with the take-off board. Subsequent research proposed that humans control step length during running by coupling the vertical impulse of a step to the optically specified time to contact with a target foothold [11]. However, further investigation revealed that the visual control of foot placement might be more complex than this simple explanation suggests [12–15] (but see [16]).

Following this initial work, numerous studies examined various aspects of the visual control of stepping over obstacles or onto footholds that lay in a walker's path [17–22]. A consistent theme throughout this line of research is that humans use visual information in a feed-forward manner to avoid obstacles or hit target footholds. This theme is corroborated by research on gaze behaviour during walking, which reveals that both humans and cats tend to direct their gaze to a point several steps in advance when walking over complex terrain [23–26]. However, much of the work on the visual control of walking focuses on environments containing a single obstacle or target foothold; far less is known about the control of foot placement when walking over extended patches of complex terrain. More importantly, research on this topic tends to oversimplify or neglect the biomechanics of human walking, which has created a barrier to understanding how the visual control of foot placement relates to the energetic efficiency of locomotion. In this study, we show how consideration of the biomechanics of human gait can lead to a more principled understanding of why people select certain footholds over others, why visual information about certain areas of the foreground must be available, and how humans achieve high levels of efficiency when walking over complex terrain.

The structure of the human musculoskeletal system is specially adapted for efficient bipedal locomotion [27–29], and the visual control of human walking is inextricably tied to the basic biomechanical features of this structure. Bipedal gait consists of two main phases—the single-support phase, when the body is supported over a single leg as the other leg swings forward, and the double-support phase, or step-to-step transition, when both legs are planted on the ground. During the single-support phase, a walker is mechanically similar to an inverted pendulum [30,31], with a large centre of mass (COM) supported over a pivot point at the ankle of the planted foot. An idealized inverted pendulum without friction or resistance is perfectly energetically efficient; no mechanical energy is lost throughout its motion. As such, because the majority of body translation during walking occurs during the single-support phase, the pendulum-like structure of the body goes far towards accounting for the efficient nature of human walking [32].

At the end of the single-support phase, the momentum of the walker's COM is directed downwards towards the ground in the direction prescribed by the arc of an inverted pendulum (figure 1). In the step-to-step transition phase of gait, the leading leg strikes the ground and performs negative work on the walker's COM. The negative work done by the leading leg and the positive work done by the trailing leg redirect the COM from a downward trajectory into the upward trajectory needed to complete the next step. Unlike the pendular motion of the single-support phase, the COM loses mechanical energy during the step-to-step transition proportional to the magnitude of the necessary redirection of the COM (α in figure 1). In humans, a push-off force from the trailing leg restores this lost energy in order to facilitate symmetry between the upcoming step and the previous one [2,3,33]. For a given step frequency, the work required to restore energy lost during the step-to-step transition is expected to increase in proportion to the fourth power of step length, which is thought to be the major determinant of the metabolic cost of human walking [9].

The dynamic walking approach provides an illuminating account of the remarkable efficiency of human walking. At each step, the location of the planted foot defines a physical system with the approximate dynamics of an inverted pendulum. By placing each step in the proper location, walkers may harness the inertia of their moving bodies in order to travel

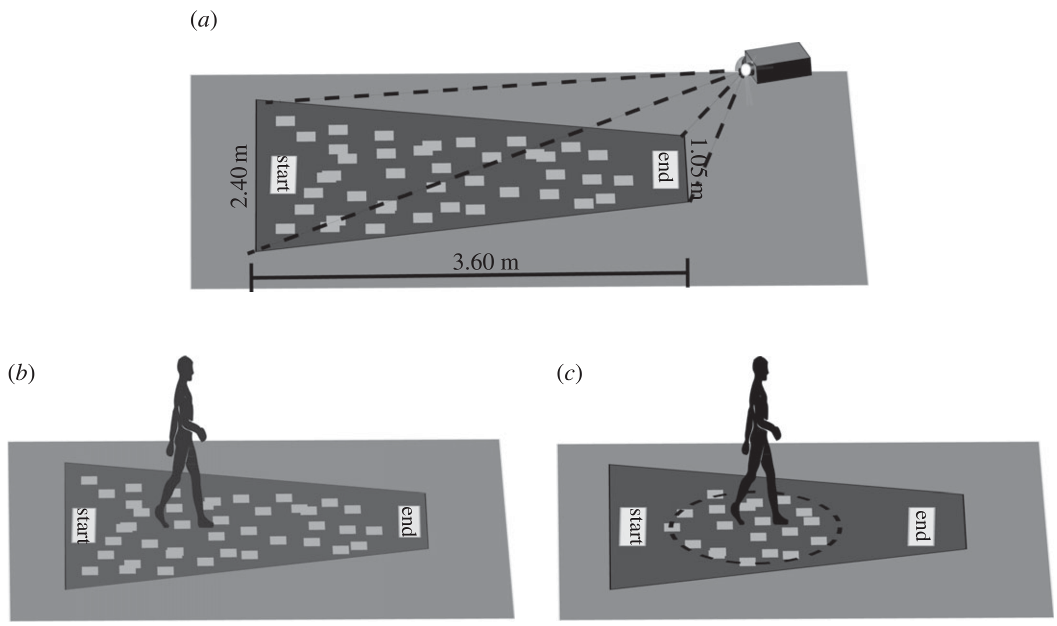

Figure 2. (*a*) Experimental set-up. An LCD projector displayed obstacles on the ground. The projector system was synchronized with a motion capture system so that subjects' collisions with the virtual obstacles could be registered and recorded. (*b*) In the full vision control condition, the entire field of obstacles was visible throughout the trial. (*c*) In the limited vision condition, obstacles were only displayed when they fell within a certain *visibility window* centred on the subject. In this study, nine different window sizes were tested, with radii ranging from one step length (0.7 × leg length) to five step lengths. The edge of the visibility window shown here (dashed circle in (*c*)) was not visible to the subject.

through the world with minimal energetic cost. When walking over flat, obstacle-free terrain, foot placement can arise naturally from the physical dynamics of the body; visual information contributes only minimally to correct for instability in the mediolateral direction [34,35]. However, in more complex terrain, such as a rocky trail, obstacles and other environmental impediments may render the desired foothold unsafe or unavailable. In such an environment, vision is necessary to select safe footholds from among the available options. The main hypothesis tested in this paper is that when walking over complex terrain, humans use visual information to choose footholds that will allow them to exploit the passive mechanical structure of bipedal walking in order to approximate the level of energetic efficiency achievable when walking over flat, obstacle-free terrain. That is to say, when walking in environments where potential footholds are constrained, humans select footholds that maximally harness the passive mechanical forces inherent to bipedal walking in order to move in the desired direction with minimal effort.

To evaluate this hypothesis, we developed an experimental set-up that simulates walking over complex terrain. An LCD projector displayed a field of semirandomly arranged obstacles across a path 3.6 m long (figure 2*a*). The projector was synchronized to a full body motion capture system, so that if a subject stepped on one of the projected obstacles, then a sound was played, and a collision was logged. Subjects were instructed to walk across the path at a brisk pace without stepping on any of the virtual obstacles. To see how well subjects exploited their biomechanical structure when performing this task, the motion of subjects' COM during each step was compared with an idealized three-dimensional inverted pendulum. The pendulum model was given the same initial position and velocity as the subject's COM at the onset of each single-support phase (identified using a technique described by Zeni *et al*. [36]; see §2), and its base was set as the location of the ankle of the planted foot (defined by a motion capture marker located on the lateral malleolus) at toe-off of the trailing leg. The pendulum moved passively under the influence of gravity and was meant to approximate the trajectory that the subject's COM would have taken if the subject had simply fallen forward under the influence of his or her own inertia. This comparison was performed for each step, and the difference between the subject's actual COM trajectory and the trajectory of the passively falling pendulum was calculated by measuring the Euclidean distance between the endpoints of the two trajectories in three dimensions. The logic of this analysis is that the smaller the endpoint difference, the more similar is the subject's motion to a passive inverted pendulum, which implies an efficient exploitation of their biomechanical structure. In addition, we also analysed subjects' energy recovery, which is a measure of the efficiency of the exchange between potential and kinetic energy of the COM during a step [31,37–42].

To investigate the role of vision in selecting footholds when walking over complex terrain, subjects walked across the field of virtual obstacles in a variety of visibility conditions. In the full vision control condition, subjects could see all of the obstacles along the entire path throughout the trial. In other conditions, obstacles were only visible within a certain distance, or *visibility window*, of the subject's position as they walked along the path (figure 2*b*,*c*). Subjects performed this task in the full vision condition and with nine different sizes of visibility window, which provided visual information about upcoming obstacles from 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 or 5 step lengths ahead. One step length was defined as 0.7 of the subject's leg length, which was found to be subjects' preferred step length during unconstrained steady-state walking [9,43]. If humans use visual information about the upcoming path to choose footholds that allow them to exploit their biomechanical structure, then as the size of the visibility window increases, subjects should be better able to exploit their inverted pendulum structure.

2. Material and methods

(a) Subjects

Twelve subjects (seven female, five male; mean age 19.4 years; mean height 1.70 m; mean weight 66.6 kg; mean leg length 0.85 m) participated in this study. Subjects were recruited from undergraduate psychology courses and received extra credit for participating. All subjects reported no motor impairments and normal or corrected-to-normal vision.

(b) Equipment

This experiment used a 14-camera motion capture system running Vicon IQ v. 2.5 software recording at 120 Hz. Subjects were fitted to a full body biomechanical skeleton based on 45 retroreflective markers placed on anatomical landmarks over tight-fitting, elastic shirt and leggings (the same template used by Diaz *et al.* [44]). Subjects completed this task barefoot to avoid irregularities caused by differences in footwear. Virtual obstacles were displayed by a Sanyo PLC-XP45 projector at a resolution of 1024 × 768 and a brightness of 3500 ANSI lumens. Details of the experimental set-up and the procedure to calibrate and synchronize the projector with the motion capture system can be found in [43].

(c) Task and procedure

After completing the procedure to fit subjects' bodies to the biomechanical template, subjects completed 10 obstacle-free walking trials wherein they were asked to walk at a brisk pace from a start position to an end position 3.6 m away. These trials were later used to normalize measures recorded in the other visibility conditions.

After completing the obstacle-free walking trials, subjects walked along the same path while trying to avoid stepping on one of 10 pseudo-random arrangements of 35 15 × 15 cm blue virtual obstacles that were projected on the floor. The obstacle field spanned the entire range of the projector, and the arrangements were chosen to be sufficiently dense to require subjects to make gait modifications to avoid obstacles while still allowing them to walk in a straight line from the start to the end position. Post hoc analysis confirmed that the mediolateral range of subjects' COM movements only increased by an average of 5.2 cm (s.d.: 0.5) relative to the obstacle-free condition, indicating that subjects were still able to walk in a straight line when obstacles were present. The projector and motion capture system were synchronized so that if subjects stepped on a virtual obstacle, a sound was played, the obstacle changed colour from blue to bright green and a collision was logged.

(d) Design

An experimental session consisted of two blocks of 110 trials each, for a total of 220 trials per subject. The first block was composed of 11 different sets of 10 trials. The first set of trials was the obstacle-free condition, and the remaining 10 sets were a random ordering of the 10 different visibility conditions described earlier, namely the full vision control condition and the nine different sizes of visibility window manipulation. The 10 sets were presented in a randomized order for each subject. The second block was identical to the first, except that the order of the 10 visibility windows was reversed. In all, there was a total of twenty repetitions of each condition.

In a previous study with a similar experimental design, we found that some subjects accommodated smaller visibility windows by decreasing their walking speed and maintaining a low collision rate with the obstacles while others maintained a normal walking speed at the cost of increased collisions [43]. To encourage more homogeneous behaviour in this study, subjects were only allowed to hit one obstacle within each trial. If a subject collided with more than one obstacle, then the trial was terminated and rerun. Subjects had 6 s to complete each trial, which ensured that they maintained an average walking speed of at least 0.6 m s^{-1}.

(e) Analyses

Data from the motion capture system were filtered using a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 7 Hz. The position of each subject's COM was found by calculating the weighted average of the position of each body segment, based on anthropometric data reported by Winter [45]. Walking speed and collisions per trial were calculated in the method described by Matthis & Fajen [43].

In order to compare subjects' movements to a passively moving three-dimensional inverted pendulum, we first used an algorithm to find the portions of the trial when the subject was in the single-support phase of gait based on a technique described by Zeni *et al.* [36]. In this method, the motion capture recording of a trial was pinned to the origin by subtracting the *XYZ* coordinates of a marker near the subject's sacrum from the *XYZ* values of the other markers. This manipulation had the effect of making the subject appear to be walking in place with their pelvis fixed to the origin. The velocity of each foot was then calculated by taking the frame-to-frame difference in position of the ankle markers on the lateral malleolus of each foot. Because the subject was moving forward throughout the entire trial, foot contact with the ground at heel strike shows up as a positive-to-negative zero-crossing in the velocity profile of the relevant foot. Similarly, toe-offs were identified by finding negative-to-positive zero-crossings in the foot's velocity profile. We discarded the first and last step in each trial in order to avoid any irregularities associated with gait initiation and termination.

At the onset of each single-support phase, immediately after toe-off, the position and instantaneous velocity of the COM were used as the initial conditions for a three-dimensional pendulum with a pivot point set at the ankle marker of the planted foot of the subject. The motion of the pendulum was simulated numerically from the Hamiltonian equations of motion by an ordinary differential equation solver in Matlab (ODE45). The model calculated the trajectory of a pendulum falling under the influence of gravity with the initial position and velocity measured from the subject's COM at the beginning of the step. At the end of the simulation, we calculated the three-dimensional Euclidean distance between the position of the subject's COM at the end of the single-support phase (immediately before heel strike) and the calculated position of the idealized pendulum model after the period of time taken in the actual step.

We also calculated energy recovery, which is a measure of the efficiency of the transduction between potential and kinetic energy during walking [31,37–42]. Percentage energy recovery (%ER) refers to the amount of work done to increase the potential energy of the COM that is recovered in the form of kinetic energy, such that

$$\%\mathrm{ER} = \frac{\Sigma\Delta^{+}\mathrm{PE} + \Sigma\Delta^{+}\mathrm{KE} - \Sigma\Delta^{+}\mathrm{TME}}{\Sigma\Delta^{+}\mathrm{PE} + \Sigma\Delta^{+}\mathrm{KE}} \times 100, \tag{2.1}$$

where $\Sigma\Delta^{+}$PE, $\Sigma\Delta^{+}$KE and $\Sigma\Delta^{+}$TME are the sums of the positive increments to potential energy, kinetic energy and total mechanical energy, respectively, during an entire gait cycle from heel strike to subsequent heel strike. Potential and kinetic energy were calculated at each frame as

$$\mathrm{PE} = mgh \tag{2.2}$$

and

$$\mathrm{KE} = \frac{1}{2}mv^2, \tag{2.3}$$

where m is the mass of the subject in kilograms, g is acceleration due to gravity (9.81 m s^{-2}), h is the height of the subject's COM above the ground and v is the velocity of the COM through three-dimensional Euclidean space. Total mechanical energy was defined as PE + KE. In an ideal inverted pendulum, PE and KE oscillate perfectly out of phase with equal amplitude so none of the positive increments to PE and KE add to the total mechanical energy of the system. Thus, $\Sigma\Delta^{+}$TME equals zero and %ER equals 100 per cent. On the other hand, if some of the positive increments to PE or KE are the result of mechanical work performed by the subject rather than a conservative exchange between potential and kinetic energy, then $\Sigma\Delta^{+}$TME will be greater than zero and %ER will be less than 100 per cent. As such, %ER provides an additional test of the efficiency with which subjects are able to capitalize on the dynamics of their biomechanical structure. Under ideal conditions, humans have been found to achieve %ER values between 65 and 70 per cent [38–40], so if the visibility manipulation does affect subjects' ability to efficiently exploit their biomechanical structure, we should expect to see a resultant drop in %ER.

(f) Statistical analyses

For each measure, we calculated the mean across trials within each condition. The effects of visibility window size were tested in SPSS using a repeated-measures ANOVA, followed by planned simple comparisons between each of the visibility windows and the full vision control condition. An application of Mauchy's test showed that the sphericity assumption was violated for all four measures, so a Huyn–Feldt correction was applied to the results.

3. Results

We compared the subjects' COM trajectory with the trajectory of a passive three-dimensional inverted pendulum in each step in the various visibility conditions. For each subject, we calculated the mean endpoint difference of all steps taken in each visibility condition. We then normalized by dividing the mean endpoint difference in each condition by the endpoint difference found in an obstacle-free walking condition (mean for all subjects: 77.3 mm, s.d.: 11.3). The results of this analysis are summarized in figure 3.[1] The univariate repeated-measures ANOVA revealed a significant main effect of visibility window size on COM trajectory endpoint difference ($F_{1.48,16.28} = 18.46$, $p < 0.01$, partial $\eta^2 = 0.63$). Planned comparisons between each visibility window condition and the full vision control condition revealed no significant increase in the difference between subjects' actual COM trajectories and the passive trajectory predicted by the inverted pendulum model when subjects could see two or more step lengths ahead ($p > 0.05$, window sizes two to five step lengths). When the visibility window was smaller than two step lengths, there was a significant increase in the predicted trajectory endpoint difference measurement relative to the full vision control condition (windows 1 and 1.5, $p = 0.01$).[2]

In addition, we found that energy recovery values (%ER) were significantly affected by the visibility window manipulation ($F_{3.54,38.92} = 9.92$, $p < 0.01$, partial $\eta^2 = 0.47$; figure 4). Simple planned comparisons between %ER in each of the

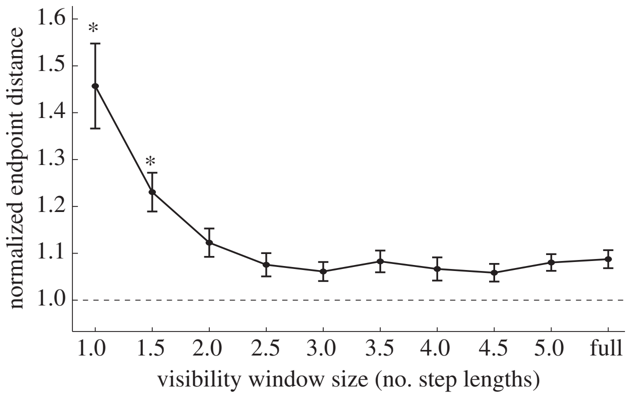

Figure 3. Mean Euclidean distance between COM at the end of each step and the predicted endpoint if the COM had followed the trajectory of an unactuated inverted pendulum with equivalent initial conditions. Values normalized by scores in an obstacle-free condition (mean: 77.3 mm, s.d.: 11.3). Asterisks denote significant deviations from the full vision control condition ($p < 0.05$). Bars indicate $\pm$ 1 s.e.m.

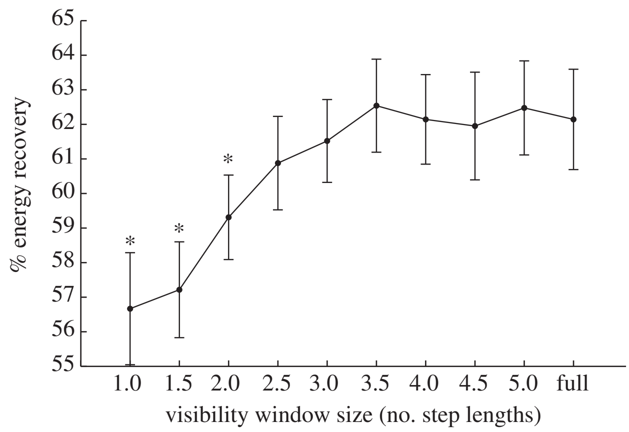

Figure 4. Mean energy recovery for all subjects in each visibility condition. Asterisks denote significant deviations from the full vision control condition ($p < 0.05$). Bars indicate $\pm$ 1 s.e.m.

visibility conditions and %ER in the full vision condition revealed a significant decrease in energy recovery in the 1.0 and 1.5 step length visibility window ($p < 0.01$), as well as in the 2.0 step length visibility window ($p = 0.047$). It is worth noting that subjects also tended to walk slower in these conditions (figure 6*b*), and %ER is known to decrease when subjects move slower than their preferred walking speed [37–38]. Thus, it is difficult to deduce from this result how much of the decrease in %ER was caused by a change in gross motor behaviour elicited by the diminished visual look ahead and how much is the consequence of the lower walking speed. However, regardless of this detail, the point remains that subjects exhibited less efficient recovery of mechanical energy in the smaller visibility window condition.

Visual inspection of subject data corroborates the results of the endpoint difference and energy recovery analyses. Figure 5 shows the mean change in COM height during the single-support phase of steps in various visibility conditions for a single representative subject. For each step in each visibility condition, COM vertical position relative to the height at toe-off was temporally normalized to the mean step duration for that condition and then pooled to determine the mean trajectory and standard deviation. In the obstacle-free

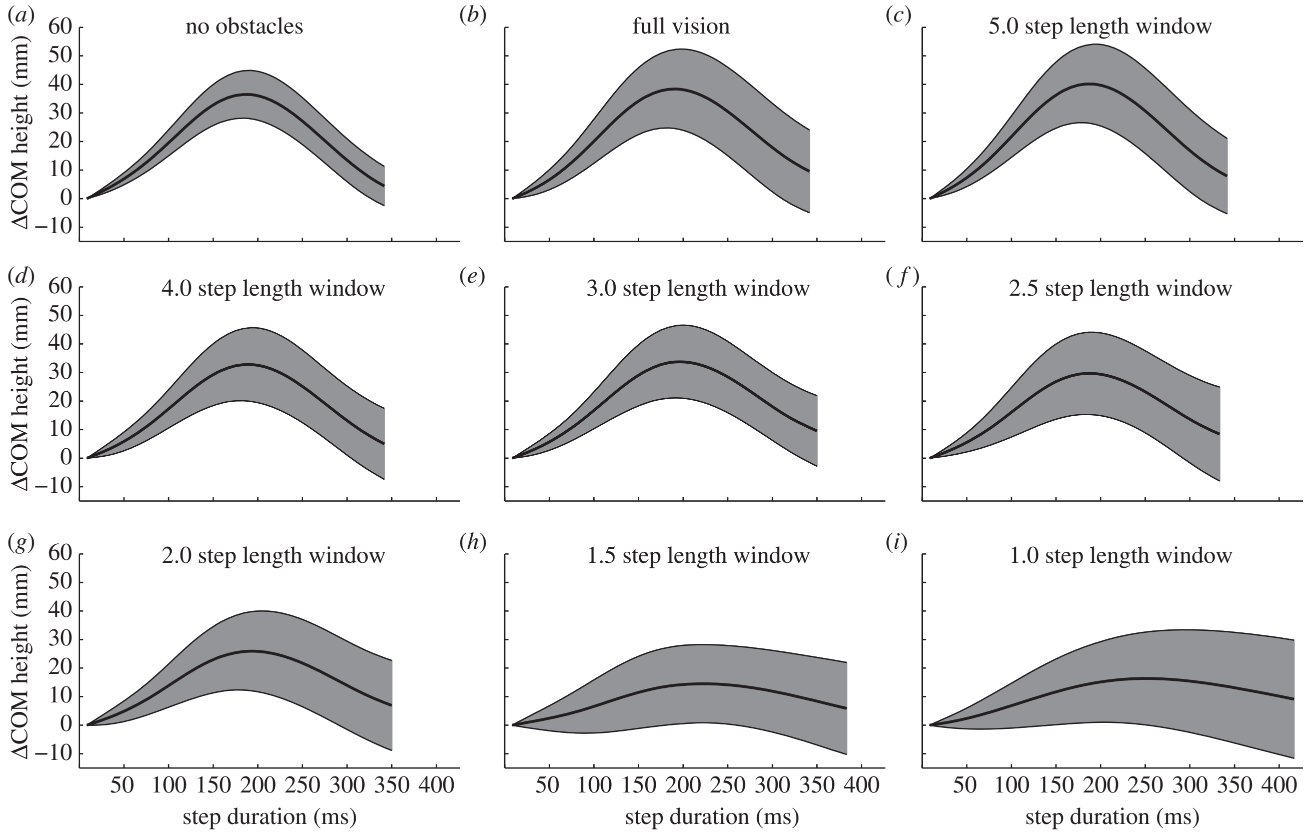

Figure 5. Mean change in COM height as a function of time during steps for a single representative subject during (*a*) obstacle-free walking and (*b–i*) a selection of the various visibility conditions. Grey regions represent $\pm$ s.d.

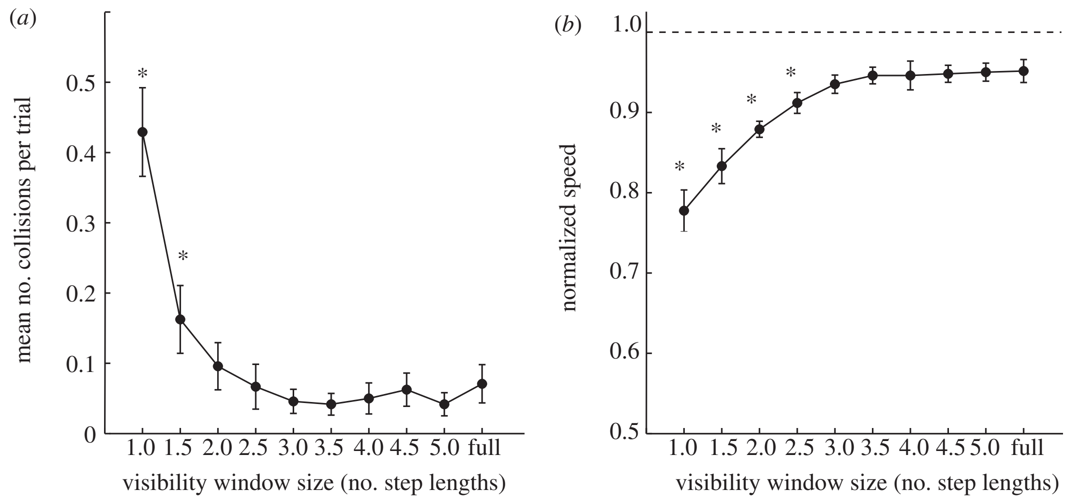

Figure 6. (*a*) Mean number of collisions per trial for each visibility condition. (*b*) Mean walking speed for each visibility condition were normalized to their scores in an obstacle-free condition (mean: 1.0 m s^{-1}, s.d.: 0.1). Asterisks denote significant deviations from the full vision control condition ($p < 0.05$). Bars indicate $\pm$ 1 s.e.m.

condition (figure 5*a*), the COM rises and then falls over the course of a step in a manner reminiscent of an inverted pendulum. This trend persists with a moderate increase in variability with the addition of the obstacle field in the full vision condition (figure 5*b*), and remains relatively unchanged in the larger visibility windows (figure 5*c–g*). However, when the visibility window is reduced to less than two step lengths, variability increases and the COM begins to follow a much flatter trajectory (figure 5*h*,*i*), indicating that the subject is not exploiting the pendular dynamics of his or her body as effectively in these visibility conditions.

In summary, analysis of subjects' COM trajectories and energy recovery values both reveal that when subjects were able to see two or more step lengths of the upcoming terrain, they were able to exploit their biomechanical structure as efficiently as they did when they had full vision. This finding is corroborated by the significant effect that was found for mean number of collisions per trial ($F_{3.19,35.09} = 24.99$, $p < 0.01$, partial $\eta^2 = 0.69$) and mean walking speed ($F_{1.75,17.03} = 26.07$, $p < 0.01$, partial $\eta^2 = 0.70$).[3] This effect is characterized by an increase in collisions with the obstacles when the visibility window is less than two step lengths (window 1, $p < 0.01$; window 1.5, $p = 0.03$; figure 6*a*) and a decrease in walking speed for windows smaller than three step lengths (windows 1–2.5, $p < 0.01$; figure 6*b*), consistent with the results of Matthis & Fajen [43]. Taken

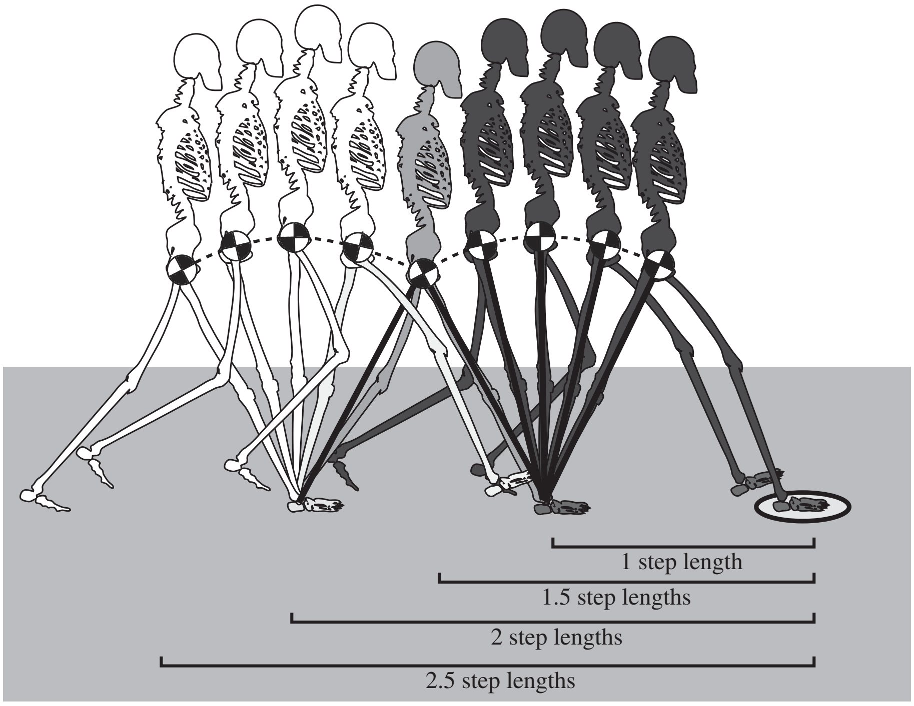

Figure 7. Consideration of the point at which the determinants of the passive trajectory of the COM for a given step are defined yields a prediction of how walking behaviour over complex terrain will be affected by the limited visibility conditions.

together, these results suggest that the critical distance for looking ahead when walking over rough terrain is approximately two step lengths.

4. Discussion

In this study, we found that as long as subjects could see two or more step lengths ahead as they walked over an array of obstacles, they were able to walk with the same level of performance as they did when they had full, unconstrained vision. Consistent with the results of Matthis & Fajen [43], the number of collisions with obstacles returns to baseline in the 2.0 step length visibility window, with small decreases to walking speed persisting into the 2.5 and 3.0 step length windows (figure 6*a*,*b*). More importantly, in the 2.0 step length window condition, the trajectory of the COM at each step was as similar to a passively falling inverted pendulum as it was in the full vision condition (figure 3), and energy recovery values were near baseline levels, with only a marginal decrease in %ER persisting into the 2.0 window (figure 4). Taken together, these results reveal that when subjects have at least two step lengths of visual look ahead, they are able to exploit their biomechanical structure as well as they do when they have full unconstrained vision.

Several studies have reported that gaze is normally directed about two step lengths ahead during walking behaviour in humans [23,26] and cats [24,25], and subjects are better able to step over a single obstacle in their path when they become visible two steps in advance [46]. In addition, certain neurons in area five of the posterior parietal cortex in cats show an increase in activity two to three steps prior to stepping over an obstacle [47]. However, no explanation has been offered for what is special about this distance. By interpreting the results of this experiment within the theoretical framework provided by the dynamic walking approach to the study of human gait, an explanation for the privileged nature of the two step length distance presents itself.

Consider a walker attempting to step onto a particular target foothold (figure 7). The most energetically efficient way to complete this task is to place the previous footstep in a location that allows the walker to fall forward ballistically like an inverted pendulum to get the COM into a position that will allow the walker to step on the target with minimal muscular intervention (figure 7, dark grey skeletons). Insofar as humans are mechanically similar to an inverted pendulum, the passive ballistic trajectory of the COM during the step leading into the targeted foothold will be determined by two factors—the location of the planted foot in the previous step and the initial position and velocity of the COM at the onset of the single-support phase. With this in mind, the critical question is: at what point during the approach to the target are these two determinants under the walker's control?

If humans only used visual information from one step length ahead, visual information about the target foothold would not be sampled until the walker is already partway through the ballistic trajectory of the previous step. This consideration may explain why subjects were less able to exploit their passive mechanical structure when the visibility window constrained vision to one step length ahead. In that condition, the terrain features that were relevant to the upcoming step did not become visible until after the two determinants of the passive trajectory of the COM in a step were already set. In that case, the only way to adjust the trajectory of the COM would be by means of energetically costly midflight muscular intervention on the COM. In the 1.5 step length visibility window, the targeted foothold becomes visible during the double-support phase of the preceding step (light grey skeleton in figure 7), which might provide subjects with the ability to tailor the push-off force from the trailing limb to adjust the initial conditions of the COM leading into the single-support phase. This may explain why normalized endpoint difference is lower and energy recovery is higher in the 1.5 step length condition relative to the 1.0 step length condition. However, with 1.5 step lengths of visual look ahead the subject still cannot control the location of the planted foot. It is not until the walker can see two or more step lengths in advance (white skeletons in figure 7) that both of the determinants (i.e. the location of the planted foot in the previous step and the initial position and velocity of the COM at the onset of the single-support phase) are under the walker's control. The walker can shift the location of the previous foothold to adjust the base of the inverted pendulum and tailor the push-off force from the trailing limb to change the initial velocity of the COM.

This account explains why subjects lost their ability to exploit their biomechanical structure when visual information was constrained to less than two step lengths. A consideration of the basic biomechanical structure of human gait reveals that a walker with two or more step lengths of visual information about the upcoming terrain has all of the information necessary to fully exploit the passive mechanical forces that are inherent to bipedal walking. Thus, two step lengths of visual information is sufficient to select footholds that will allow a walker to approximate the level of energetic efficiency achievable when walking over flat, obstacle-free terrain.

The experimental protocol was approved by the Institutional Review Board at the Rensselaer Polytechnic Institute, and all subjects gave written informed consent prior to participating.

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Endnotes

[1]We also performed a version of this analysis that measured the average difference between the two trajectories and found equivalent results. However, because the distance between early stages of the trajectories will always be very small, we believe that the endpoint distance provides a better characterization of the data.

[2]There was also a small but significant *decrease* in endpoint difference for windows 3.0 and 4.5 ($p = 0.01$). However, the extremely small magnitude of this decrease (-0.03 and -0.02, respectively) and the direction of the difference make it difficult to interpret this result. Thus, although the statistical tests are significant for these windows, we do not believe that the differences are meaningful.

[3]As with the endpoint distance, we normalized each subjects' walking speed by the speed they walked in the obstacle-free condition (mean for all subjects: 1.0 m s^{-1}, s.d.: 0.1).

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