Off on the wrong foot: Local features in biological motion

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Abstract. Biological-motion perception consists of a number of different phenomena. They include global mechanisms that support the retrieval of the coherent shape of a walker, but also mechanisms which derive information from the local motion of its parts about facing direction and animacy, independent of the particular shape of the display. A large body of the literature on biological-motion perception is based on a synthetic stimulus generated by an algorithm published by James Cutting in 1978 (*Perception* **7** 393 – 405). Here we show that this particular stimulus lacks a visual invariant inherent to the local motion of the feet of a natural walker, which in more realistic motion patterns indicates the facing direction of a walker independent of its shape. Comparing Cutting's walker to a walker derived from motion-captured data of real human walkers, we find no difference between the two displays in a detection task designed such that observers had to rely on global shape. In a direction discrimination task, however, in which only local motion was accessible to the observer, performance on Cutting's walker was at chance, while direction could still be retrieved from the stimuli derived from the real walker.

1 Introduction

Humans have a striking ability to detect and extract information from the motion of living creatures. A major tool to study biological motion was introduced into visual psychology by Johansson (1973). His point-light displays, which consist of only a few dots moving along with the major joints of a human in motion, elicit a clear percept of actor and action without being confounded with other cues, such as clothing or facial information. The ease with which the human visual system retrieves information from these degraded displays reflects a number of different processing levels. Troje (2008a) has suggested that the complex phenomenology of biological-motion perception can only be understood if we carefully distinguish between two different processes in particular. One uses the local motion signals directly, in particular for tasks such as detecting the presence of an animal or inferring its orientation, while another integrates the articulated motion of a body to infer its structure and how that structure deforms over time.

The majority of work in the field of biological-motion perception has focused on this second process. Early studies proposed models for how hierarchical structures of limbs and joints could be determined by subtracting motion trajectories from one another (Cutting 1981; Johansson 1973, 1976). Later it was shown that the global form can be recovered even when the local motion of the dots is rendered entirely uninformative. Point-light displays of walking human figures can still be detected, at least to some degree, when masked by randomly displaced copies of the motion of the dots making it up (Cutting et al 1988), indicating that the global form is sufficient for detection. On the other hand, this 'scrambled walker mask' did prove to be a much more effective mask than any of the other types of masks used in the study. The loss of local motion as a cue to the presence of a walker caused a substantial decrease in performance, suggesting that it does play an important role.

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Further experiments with the scrambled walker mask showed that the global structure of the point-light display is sufficient to determine the direction of walking, and to show the pronounced inversion effect that seems to be characteristic of biological-motion processing (Bertenthal and Pinto 1994). Similar results were observed when local motion patterns were eliminated in a different way, namely by randomly repositioning the dots on the body in every frame of a motion sequence (Beintema et al 2006; Beintema and Lappe 2002; Neri et al 1998).

In contrast to this emphasis on deriving the global, articulated structure from the point-light display, some researchers have asked whether there might be valuable information used by the visual system in the local motion alone. Mather et al (1992) tested performance on a direction task (asking participants whether the walker was facing left or right) when sets of dots were removed from the point-light display. Removal of shoulder and hip dots, or elbow and knee dots, had no effect on performance (which was approximately 90% correct), but removing the wrist and ankle dots while leaving all other dots resulted in a reduction of performance to near-chance levels. Troje and Westhoff (2006) also found evidence that motion of the extremities is important in biological-motion perception. However, while the stimuli used by Mather et al (1992) still retained most of the coherence of their shape, Troje and Westhoff used spatially scrambled walkers in their study which entirely lacked coherent global form. They found that even though observers had no idea what kind of creature they were seeing, they had a clear percept of facing direction—but only if the displays were shown in upright orientation. A subsequent experiment showed that this inversion effect was dependent only on the orientation of the trajectory of the ankle dots, while no effect resulted from inverting any of the other trajectories. The results were not limited to human motion but were also obtained with point-light displays derived from a walking pigeon and from a walking cat.

Troje and Westhoff (2006) suggested that cues contained in the local motion of an animal's feet may play a role as a general detection system that signals the presence of a terrestrial, articulated animal in the visual environment (see also Johnson 2006). They hypothesised that such a system might be evolutionary, old, and possibly innate rather than being based on individual learning. Some evidence for this idea has since been demonstrated. For instance, Vallortigara and Regolin (2006) have shown that newborn chicks already respond preferentially to upright, but not to inverted, biological motion, but that the particular shape of the point-light animal (cat or chicken, coherent or scrambled) has no effect on this preference behaviour (Vallortigara et al 2005). Simion and colleagues (2008) have shown that 2-day-old human neonates also prefer upright biological motion over inverted biological motion. They used point-light displays of chicks, and therefore a shape which is probably as meaningless to a 2-day-old infant as a scrambled display. Finally, Chang and Troje (2008) showed that adult observers consistently rated scrambled point-light displays (of humans, pigeons, and cats) as more animate when presented upright rather than inverted.

In all these studies, observers responded either to scrambled biological motion or to biological motion carried by structures they are entirely unfamiliar with. All they could use was the local motion of the trajectories of individual dots, most likely the dots representing the feet. Since such local motion alone can specify the direction of walking, affect the impression of animacy, and control preference behaviour of chicks and human neonates, we must consider the processing of local motion signals as an essential component of biological-motion perception. Destroying the structure by spatially scrambling the walker cannot therefore be considered a means to eliminate the biological aspect of the motion, as has been assumed in many psychophysical studies (eg Fujimoto 2003; Thornton et al 1998; Verfaillie 2000) and functional imaging studies (eg Vaina et al 2001).

One reason why the important role of local motion has been overlooked for a long time relates to the way many researchers in the field have generated their biological-motion stimuli. In 1978, James Cutting published a paper in which he described a simple algorithm that would create a point-light display of a human walking in sagittal view. He was inspired by work in speech recognition that involved synthesising auditory stimuli to determine which features produce a particular judgment in the listener about what phoneme they are hearing, and wanted to create a point-light stimulus that could be manipulated in a similarly principled way. Using his walker stimulus, Cutting (1978) showed that changing the synthesised relative motion of the hips and shoulders affected observers' judgment of the gender of the figure, providing evidence for the earlier conjecture (Kozlowski and Cutting 1977) that the centre of movement is the critical invariant which discriminates between male and female walking. Cutting's walker was a breakthrough for biological-motion research because it allowed for both ease of generation of biological motion displays in laboratories around the world and for unprecedented control over the spatial and temporal characteristics of the display. The walker was generated by a FORTRAN program which animated each of the 13 dots with some combination of ellipsoid and pendular motion, defined within the hierarchical organisation of an articulated body. The trajectories of shoulders and hips were modeled as simple ellipses, while the elbow and knee motions were modeled as pendulums with the motion of the shoulders and hips, respectively, added to them. He qualitatively compared the resulting motion pattern to existing knowledge about human gait (Murray 1967), but the final parameter settings were chosen by eye. Many important results have been established with this display, and even 30 years after its publication Cutting's walker is still widely used (eg Hiris 2007; Lange and Lappe 2007; Neri et al 1998; Saygin et al 2008; Thornton and Vuong 2004).

However, while the general shape of Cutting's synthetic walker resembles point-light displays derived directly from human walking, it differs in important ways from recordings of real human motion, particularly in the critical invariants contained in the kinematics of the feet (see figure 3). Runeson (1994), among others, warned that such synthesised displays may be missing information about dynamics, in particular the effect of gravity and the ways the organism's musculoskeletal system responds to it. Given the role that the feet seem to play (Mather et al 1992; Troje and Westhoff 2006), we expect that these differences seriously affect the invariants in the local motion that convey direction and animacy in more natural displays. We assume that the wide usage of Cutting's walker is also the reason why the presence of these cues in normal scrambled biological-motion displays was overlooked for such a long time.

In the first experiment of the present study, we compare the performance of human observers in a direction-discrimination experiment between Cutting's walker and a walking display derived from recorded human motion, which we will refer to as the BML (BioMotionLab) walker (Troje 2008b). Both coherent and scrambled versions of the walkers were used, but the critical condition is the one in which scrambled walkers are presented and so decisions must be based entirely on local motion cues.

Whereas in the first experiment we presented local motion without global motion, in the second experiment we chose a paradigm that makes available global motion but not local motion. Specifically, we employed a detection task, with coherent versions of the walkers embedded in a mask made of scrambled walkers. Differences as to the presence of the critical cues in the local motion should only affect experiment 1, and, specifically, the condition in which scrambled walkers are used.

2 Methods

2.1 *Participants*

Twelve people participated in the experiment (four male, eight female, aged 17–44 years, mean = 20.2 years), all had normal or corrected-to-normal vision. All but one subject had no experience with biological motion and point-light stimuli, and all were naive with regard to the purpose of the study. All but one were undergraduate students at Queen's University. They received course credit for their participation.

2.2 *Stimuli*

Displays consisted of point-light walkers presented in the centre of a 17-inch CRT monitor, operated with a 100 Hz refresh rate. Each point-light display subtended 6 deg of visual angle vertically, with the observer's viewing distance fixed at 80 cm by means of a chin-rest. The displays consisted of eleven white dots on a black background, representing a sagittal view of the head, elbows, wrists, knees, and ankles, as well as one shoulder and one hip, of a human walking without forward displacement, as if on a treadmill. Gait frequency was 0.93 Hz.

Scrambled walkers were produced by subtracting from each trajectory its mean position, and then adding to it a random constant position which would place it within a rectangular range of 4 deg × 6 deg of visual angle. In addition, the trajectory was also randomly offset in time. The result was that the local motion of each dot's trajectory remained unchanged, while its position within the display and its temporal phase with respect to the other dots was randomised.

Two different masks were used. The scrambled mask was based on a similar technique used to create the scrambled walker. The only difference was that, depending on the required number of masking dots, multiple copies of the scrambled walker were used, and the dots comprising these walkers were randomly distributed over a rectangular range of 9.6 deg × 9.6 deg of visual angle. Scrambled masks were always made from the same walker (BML walker or Cutting walker) they were intended to mask. The random-dot mask was produced by randomly placing stationary dots within this 9.6 deg × 9.6 deg mask area. Each dot was displayed for 300 ms at a given location, after which it disappeared and then reappeared elsewhere.

The point-light walkers were generated by two different methods.

2.2.1 *Cutting's walker.* The animation of Cutting's walker was created following the algorithm published in Cutting (1978).

2.2.2 *The BML walker.* The BML walker was produced from the walks of 50 women and 50 men obtained by means of a motion-capture system. Participants were instructed to walk at a normal pace in a straight line for several steps. Each participant had 41 reflective markers attached to his or her body, which were tracked in 3-D space by an array of nine high-speed (120 Hz) cameras making up part of a motion-capture system (Vicon 512, Oxford Metrics). A biomechanical model of the human body was then applied to estimate the movement over time of 13 'virtual markers' located inside the body. They included the joint centres of the shoulders, elbows, wrists, hips, knees, and ankles, as well as the centre of the head. One of the shoulder and one of the hip points were discarded, resulting in an 11-dot display, with each point corresponding to a point in Cutting's walker. The forward component of the movement was subtracted. Each trajectory was then transformed into a discrete Fourier expansion. All but the average position and the first two harmonics, which together represented 98% of the variance, were discarded, resulting in a smoothed, continuous walking loop. The final BML walker was obtained by averaging these Fourier representations over all 100 individuals (for details see Troje 2002, 2008b).

2.3 Procedure

All participants completed both the detection task and the direction task in two separate blocks. The order of the two experiments was counterbalanced, so that half of the participants started with the direction task first and the other half started with the detection task. Before each experiment participants read the instructions and then completed several practice trials to get familiar with each task.

2.3.1 *Direction task.* In each trial either the BML walker or Cutting's walker was displayed facing to the left or to the right. The walker was either presented in its coherent shape or was scrambled. We included trials with coherent walkers to make the task more rewarding for our participants. The critical condition, however, was the one employing scrambled biological motion in which only local motion cues can be used to solve the task.

In all cases, walkers were embedded in a random-dot mask consisting of 50, 200, or 750 dots. Participants were instructed to press the left or the right arrow key as quickly as possible to indicate the direction in which the walkers seemed to face. Each trial was shown until a key was pressed, or until a maximum duration of 1 s. Between trials, the screen remained blank for 1 s. No feedback was provided. There were 20 repetitions for each cell in our design, resulting in a total of 240 trials (2 walkers × 2 directions × 3 mask densities × 20 repetitions).

2.3.2 *Detection task.* A two-alternative forced-choice design was used. Each trial consisted of a pair of displays shown sequentially. Each display was presented for 1 s and contained a scrambled walker mask with 50, 100, or 250 masking dots. In addition, either the first or second interval also contained a coherent walker—either the BML walker or Cutting's walker. Walkers were shown in sagittal view, facing randomly either to the left or to the right. Participants pressed the left arrow to indicate that the walker was in the first interval, or the right arrow key to indicate the second interval. There were 20 repetitions for each condition, for a total of 240 trials (2 walkers × 2 intervals × 3 mask densities × 20 repetitions).

3 Results

3.1 Direction task

The results of this task are shown in figure 1. For coherent walkers, direction errors were low and similar between the two walker types. For scrambled walkers, direction errors were generally higher. In this condition, performance with Cutting's walker was at chance, while error rates fell below chance level for the BML walker. Mask density seemed to affect the coherent walkers much more than the scrambled versions.
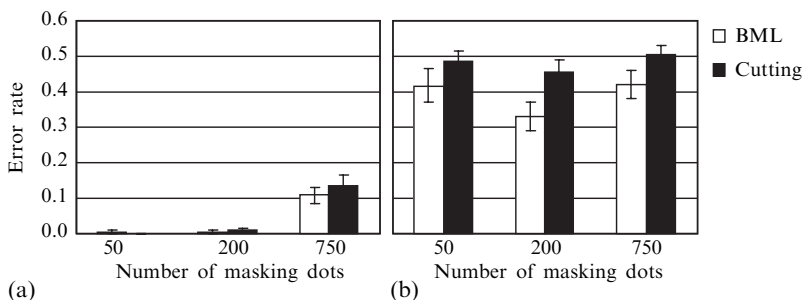

Figure 1. Mean error rates across twelve participants for the direction task. (a) The BML walker and Cutting's walker presented unscrambled; (b) the BML walker and Cutting's walker presented spatially scrambled. In the unscrambled, 50-masking-dot BML condition, all participants had an error rate of 0. In all conditions the masks consisted of static limited-lifetime dots. The error bars represent ±1 SEM.

A three-way repeated-measures ANOVA conducted on error rates confirmed these observations. It showed significant main effects of walker type ($F_{1,11} = 15.92$, $p < 0.01$), scrambling ($F_{1,11} = 303.26$, $p < 0.001$), and mask density ($F_{2,22} = 11.31$, $p < 0.001$). There was also a significant interaction between walker type and walker scrambling ($F_{1,11} = 9.56$, $p < 0.05$), and a significant interaction between scrambling and mask density ($F_{2,22} = 4.13$, $p < 0.05$). All other interactions were non-significant. A simple main effects analysis was conducted to assess the effect of walker type within the scrambled walker and coherent walker conditions. There was no significant difference between walker types in the coherent condition ($F_{1,11} = 0.44$, $p = 0.52$), but there was a significant difference between walker types in the scrambled condition ($F_{1,11} = 16.02$, $p < 0.01$), confirming that the scrambled BML walker still retained information about its facing direction while Cutting's walker did not. A one-sample t-test was conducted for Cutting's walker within the scrambled condition. The average error rate was not significantly different from 50% ($t_{11} = 0.84$, $p = 0.42$). The interaction between walker scrambling and number of masking dots was due to a significant simple main effect of number of masking dots within the coherent walker condition ($F_{2,22} = 32.54$, $p < 0.001$), but there was no effect of number of masking dots in the scrambled walker condition ($F_{2,22} = 2.36$, $p = 0.118$). The same pattern of results was seen in a three-way repeated-measures ANOVA performed on d' values [significant effects of walker type, walker scrambling, and number of masking dots, with an interaction between walker type and walker scrambling ($F_{1,11} = 7.98$, $p < 0.05$), as well as between walker scrambling and number of masking dots ($F_{2,22} = 6.18$, $p < 0.01$), with the average d' for the scrambled Cutting walker not significantly different from 0 ($t_{11} = 0.86$, $p = 0.41$)].

3.2 Detection task

The results of this task are shown in figure 2. Larger numbers of masking dots caused more errors, but there was no difference between the BML walker and Cutting's walker. A two-way ANOVA conducted on error rate confirms this observation. There was a significant effect of number of masking dots ($F_{2,22} = 28.55$, $p < 0.001$), but no other main effect or interaction. The same pattern of results was seen in a two-way repeated-measures ANOVA performed on d' values (effect of masking dots, $F_{2,22} = 28.89$, $p < 0.001$; effect of walker type, $F_{1,11} = 0.02$, $p = 0.89$).
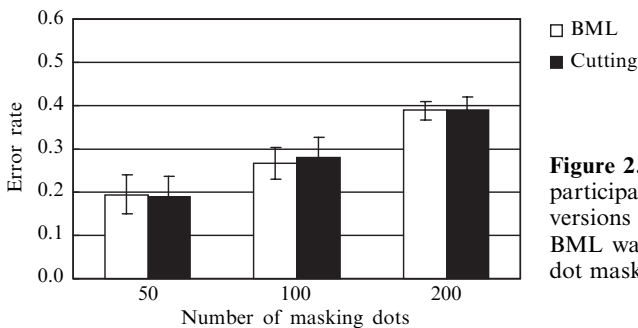

Figure 2. Mean error rates across twelve participants for the detection task. Coherent versions of either Cutting's walker or the BML walker were presented in a scrambled dot mask. The error bars represent ±1 SEM.

4 Discussion

Our results demonstrate that Cutting's (1978) walker lacks the cues that signal facing direction in scrambled displays derived from recordings of natural locomotion patterns such as the BML walker. Performance on the detection task, where only the global shape was available to identify the presence of the walkers, did not differ between the walker types.

What are the differences between the walker types that account for the differences in performance? The most obvious differences are in the feet (as represented by the ankles in the motion-capture recordings), which Troje and Westhoff's (2006) findings suggest are the principal carriers of direction information. A plot of the trajectory of the ankle (figure 3) shows the similarity between the foot movement of the BML walker and that obtained from typical motion-capture recordings. The feet of Cutting's walker have several differences visible in this figure. Where the feet of the BML and the real walkers are stopped abruptly by the ground, the foot of Cutting's walker appears to extend slightly below the ground. The Cutting foot lacks at least in part the horizontal asymmetry of the teardrop shape of the real foot movement, and assumes a more symmetrical shape, almost approaching a horizontal figure 8. Examining the vertical component of the movement alone, a plot of position, velocity, and acceleration over time (figure 4) reveals more differences. During the swing phase, the feet of Cutting's walker decelerate less sharply and for a longer duration. The longer deceleration of Cutting's walker also reflects a longer relative duration of the swing phase within the gait cycle.
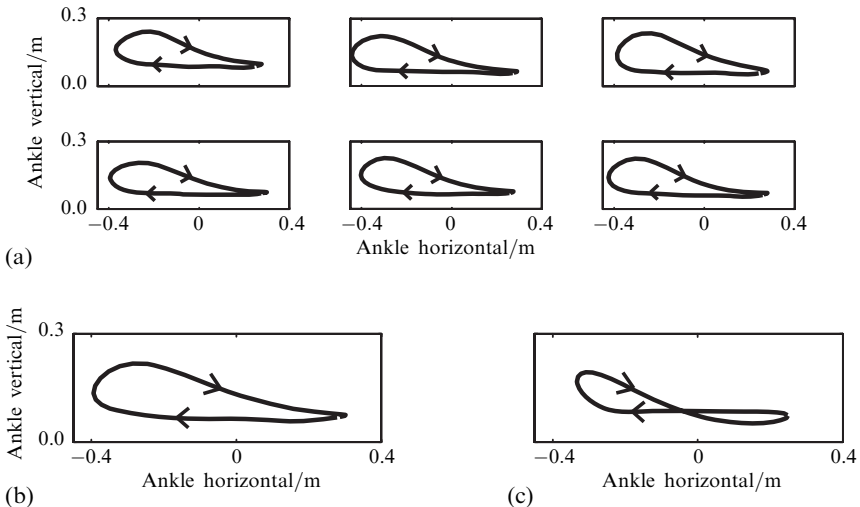

Figure 3. Plots of the trajectory of the ankle movement of a walker seen in sagittal view and facing to the right. Overall forward displacement was subtracted, leading to a treadmill-like display. (a) The ankle trajectories of six randomly selected recordings from the database used to generate the BML walker. (b) The ankle trajectory of the BML walker. (c) The ankle trajectory of Cutting's walker.

For the kinematics along the horizontal axis, which are likely more directly relevant to the direction-discrimination task, there are at least two noticeable differences in the foot acceleration between the two types of walkers (figure 5). There is an additional small peak in acceleration at the start of the swing phase of the BML walker's gait cycle, and a sharper deceleration just after the end of the swing phase, as the heel strikes the ground. Though these differences can be clearly seen in comparing the acceleration plots for the BML walker and Cutting's walker, they are only subtly visible in the plot of horizontal position. In addition, the motion of the foot of Cutting's walker on the horizontal axis is more symmetrical with respect to time; by comparison the feet of the BML walker form more of a 'saw-tooth' pattern, which may assist in cueing direction.

These differences in the kinematics along both the vertical and the horizontal axes are particularly relevant in light of the recent finding by Chang and Troje (2009) that the pattern of acceleration plays a key role in determining the direction of feet
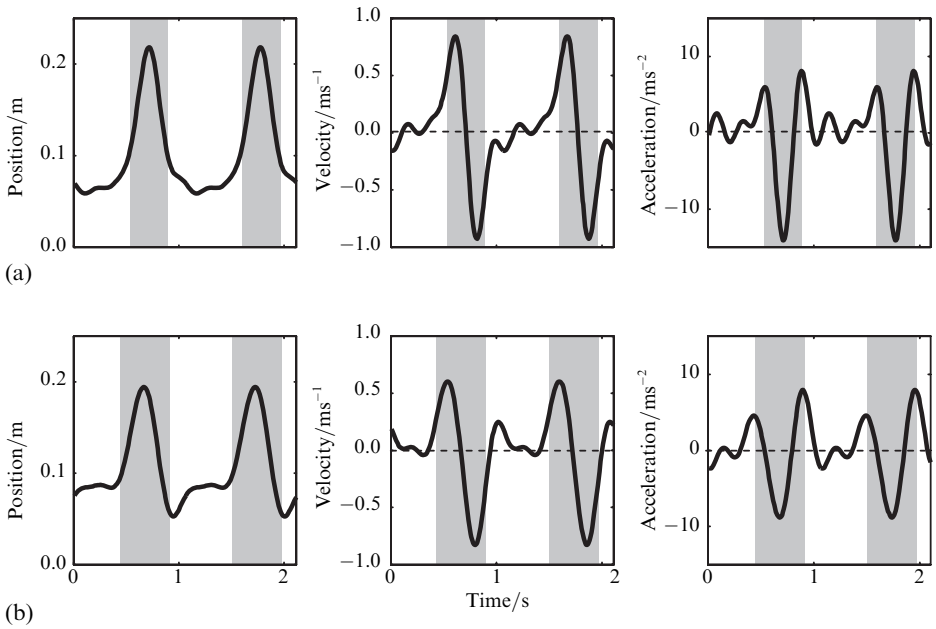
Figure 4. Vertical displacement, velocity, and acceleration over two full gait cycles for (a) BML walker, and (b) Cutting's walker. Shaded regions indicate swing phases and white regions indicate stance phases.
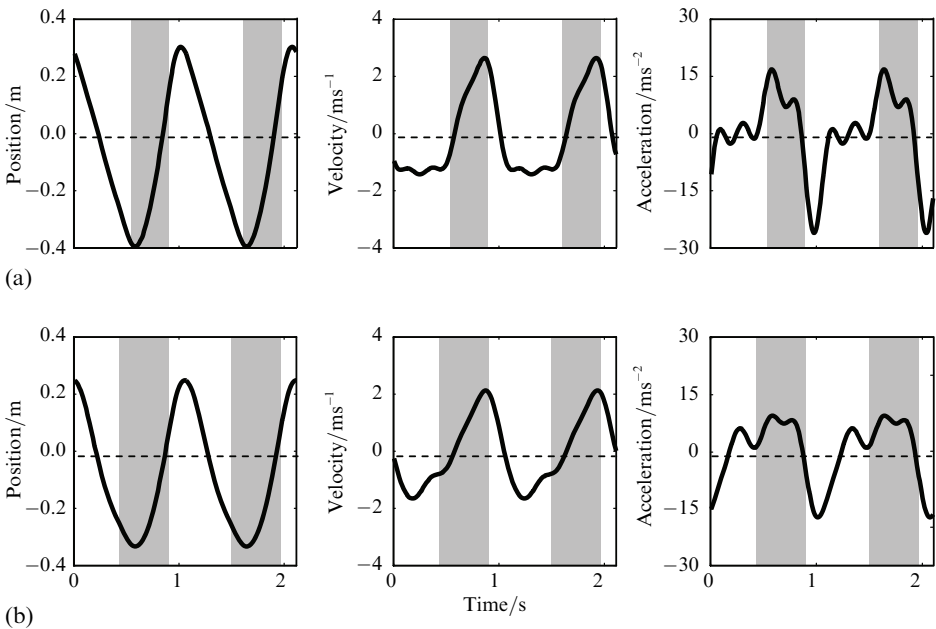

Figure 5. Horizontal displacement, velocity, and acceleration over two full gait cycles for (a) BML walker and (b) Cutting's walker. Shaded regions indicate swing phases and white regions indicate stance phases.

motion in isolation. They showed that the apparent facing direction of a point-light display consisting of feet motion only (of the BML walker, but also from point-light displays of other animals) could be determined from only brief segments of the motion of the two ankle dots, and that this ability was hampered when the dot motion was presented upside down. However, when the characteristic acceleration profile was

removed by replacing the motion with a constant-velocity tracing of the same trajectory, there was no longer an effect of inversion on performance. They concluded that observers make use of the characteristic pattern of acceleration which the feet follow as the walker responds to gravity in an energy-efficient way. From the present results, it appears that at least some of the features that characterise the typical acceleration profile of a natural foot are missing in Cutting's walker.

Johansson (1976) first demonstrated the sensitivity of the human visual system to deviations from normal biological motion, finding that all of his observers could tell that a point-light display was produced by a puppet rather than by a person in less than 500 ms. Runeson and Frykholm (1983) showed that observers can derive the true weight of a box by seeing it lifted, even if the lifter tries to deceive the observer by acting as though the box is heavier or lighter than it actually is. Runeson (1994) argued that to ensure point-light displays contain all the information that may be perceptually relevant, recordings of real motion should be used, and "we must require that even its finer details are intact" (page 392). He pointed out that Cutting's walker has "no involvement of dynamic factors such as mass, elasticity, energetic processing, or neural mechanisms, nor are any of the law of motion taken into account" (page 392).

The finding that direction of the scrambled walker could be determined for the BML walker but not for Cutting's walker may explain a discrepancy between two previous results. Troje and Westhoff (2006) found a 64% accuracy, significantly above chance, for the direction task using the scrambled walker masked by random flickering dots, whereas Lange and Lappe (2007) found that participants in their study viewing a scrambled walker display did not perform significantly better than chance on the direction task. Troje and Westhoff used the BML walker to generate its point-light display, while Lange and Lappe used Cutting's walker.

Increasingly, biological-motion perception studies use motion-capture-derived stimuli (eg Ikeda et al 2005; Jastorff et al 2006) as this technology becomes more accessible. New techniques other than conversion to a point-light display are also being explored for controlling the non-motion cues in a scene (eg Kuhlmann and Lappe 2006). However, there is still a large body of research which is based on Cutting's walker. For most of these studies, Cutting's walker is probably an appropriate approximation. In particular, it can be used to study the mechanisms underlying perceptual organisation of the individual dots into a coherent shape. However in other cases the use of Cutting's walker may have produced results different from the ones a real walker would have revealed. Caution needs to be exercised particularly in experiments in which a scrambled walker is used as a 'non-biological' control stimulus in order to eventually conclude that a phenomenon must be based exclusively on coherent structure rather than on local information. For instance, Fujimoto and Yagi (2008) showed that a coherent walker induces apparent motion in a flickering background, but a scrambled walker does not. The difference between the two displays is certainly the presence versus the absence of coherent shape, and it can therefore be concluded that coherent shape is able to induce background motion. However, from this experiment it cannot be excluded that information in the local motion (for instance, of the feet) could also induce background motion. Other examples of experiments that follow a logic that is potentially vulnerable to the particular kind of walker used are the work of Thornton and Vuong (2004) on the effect of coherent and scrambled flanker stimuli, and the work of Saygin et al (2008) on sensitivity to audiovisual asynchrony in point-light displays.

Further studies will investigate in detail which aspects of the motion of the extremities are used to determine direction, and what role they play in detection of biological motion, in biological-motion perception in the visual periphery, and in perception of animacy. Our conclusion from the present study is that Cutting's (1978) walker differs in systematic and perceptually relevant ways from real human motion.

Invariants contained in the local motion alone, without the possibility of deriving structure from the display, can play an important role in perception of biological motion, but this role may not be detected in experiments that employ Cutting's walker since it does not represent these invariants realistically.

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