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Perception of Gait

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Our ability of perceive the identity and naturalness of a human gait is examined in a series of four experiments involving computer-animated stick figures. The results indicate that the perceived naturalness of a walking or running gait can be influenced by the motion of any limb segment, but the perceived identity of these gaits is primarily determined by the movements of the lower leg (i.e., the tibia). The results also demonstrate that a perceptually salient walking gait can be transformed into running (or vice versa) by adding or subtracting a constant value to the angle of the lower leg over the entire step cycle. The size of this constant value is affected by the shape of the lower leg angle function and the motion of other limb segments.

In a recent series of experiments performed at the University of Uppsala, Gunnar Johansson elegantly demonstrated the extraordinary ability of human observers to perceive biological motion. Johansson (1973) placed small flashlight bulbs on the shoulders, elbows, wrists, knees, and ankles of a human actor and made a motion picture film as the actor moved about in a darkened room. The film was then presented to naive human observers. In the opening scene when the actor sat motionless in a chair, the observers perceived nothing more than a random constellation of disconnected elements. As soon as the actor began moving, however, they immediately perceived that the lights were attached to an otherwise invisible human being.

Johansson's purpose for performing this experiment was to provide a vivid demonstration of how complex motions are perceived within a hierarchical framework of nested frames of reference—a process he has referred to as "perceptual vector analysis." Although the experiment was certainly successful in this regard, the results also provided an equally vivid demonstration of another aspect of human motion perception—namely, our ability to identify different categories of motion, such as running, walking, or jumping. Subsequent research on "point-light walker" displays has demonstrated this ability even more clearly. For example, Johansson (1976) has shown that it takes less than 400 msec for observers to determine whether they are viewing a real human actor or a wooden puppet, and that they can accurately distinguish between running, walking, and jumping, both forward and backward. Other researchers have shown that point-light displays provide sufficient information to specify the gender of an individual (Barclay, Cutting, & Kozlowski, 1978; Cutting, 1978a; Cutting, Proffitt, & Kozlowski, 1978; Kozlowski & Cutting, 1977), the identity of a friend (Cutting & Kozlowski, 1977), or the amount of force that is exerted when a person lifts a heavy weight (Runeson & Frykholm, 1981). In a related experiment, Bassili (1978) has demonstrated that the coordinated movement of isolated points of light can uniquely specify particular facial expressions, such as frowning or smiling.

Little is known about how the visual system is able to achieve these remarkable accomplishments. Cutting (1978a) and Cutting et al. (1978) have provided convincing evidence that an individual's gender is specified by the center of moment defined by the movements of the shoulder and hips. Hoenkamp (1978) has also suggested some possible parameters that may play a role in gait identification. However, with these exceptions (see also Cutting, 1981), the precise nature of the perceptual information provided by human movement remains a mystery.

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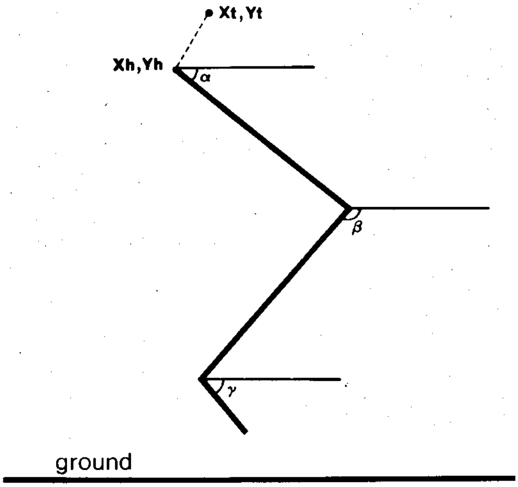

Figure 1. The seven variables that were manipulated over time to produce the patterns of motion examined in the present experiments. (The position of the torso [Xt,Yt] was not depicted in the actual displays, but it served as a frame of reference for the movements of the other limb segments. The specific functions that were used to control these variables are given in Figures 2–7.)

It is important to recognize that the theoretical issues raised by Johansson's demonstrations are not restricted to point-light displays. The identification of complex patterns of movement is a fundamental aspect of perception that is often taken for granted in our day-to-day experiences. When observing the behavior of another person, for example, we can immediately discern whether the individual is walking, running, marching, skipping, jumping, or limping. The list of verbs for categorizing human motion is large, and the list becomes even larger when we consider the possible motions of other animals. The perceptual salience of subtle distinctions among different patterns of movement is perhaps most clearly evident when observing a pantomimist or an expressive dancer.

The research reported in the present article is an attempt to explore some of the stimulus parameters that distinguish different patterns of motion—specifically, human running and walking. The basic methodology, adapted from Cutting (1978a, 1978b, 1981) and Hoenkamp (1978), is to simulate these gaits using computer-animation techniques. Several differences between running and walking are described, and their respective significance for the perception of gait are evaluated empirically using both static and dynamic displays.

Experiment 1

Method

Subjects. Twenty-two observers, all undergraduates at the University of Connecticut, participated in the experiment to fulfill the requirements of an introductory psychology class.

Apparatus. Stimuli were generated by a Nova minicomputer and were displayed using a Grinnell graphics system on a 17-in. (43 cm) Conrac video monitor. The displays had a resolution of 512 × 512 pixels, which was limited by the size of the video frame buffer.

Stimuli. Each stimulus consisted of a pair of three connected line segments, whose relative positions and orientations changed over time in a cyclical manner. Phenomenally, these segments appeared as a pair of human legs that either walked or ran on an invisible treadmill. When presented on the display screen, the upper and lower leg segments were 2.75 in. (7 cm) long while the foot segment was .55 in. (1.4 cm) long. The overall configuration of different limb segments at any given moment in time had seven degrees of freedom, which are represented in Figure 1.

In generating the displays, these seven degrees of freedom were manipulated in a hierarchical fashion. First, the position of the torso (Xt, Yt) was moved up, down, forward, and backward relative to the ground. Although the torso was not depicted in the actual displays, it served as a frame of reference for the motion of the other limb segments. Next, the position of the hip (Xh, Yh) was moved up, down, forward, and backward relative to the torso. The angle of the upper leg (α) was rotated about the hip, the angle of the lower leg (β) was rotated about the knee, and the angle of the foot (γ) was rotated about the ankle. The corresponding limb segments on each leg were moved identically except that they were 180° out of phase.

The values of these seven variables at any given moment uniquely determined a particular configuration of limb segments. During some portions of the step cycle, however, their values were computed indirectly using other variables, which were more convenient to manipulate. These other variables included the knee angle (δ) formed by the upper and lower leg, and the horizontal and vertical positions of the knee, ankle, and toe.

The step cycle was divided into 120 time periods, which were grouped into three distinct units or phases called the *transfer phase*, the *landing phase*, and the *drive phase*. (The landing and drive phases are referred to collectively as the *support phase*.) The variation over time of any given relation between different limb segments did not necessarily remain the same from one phase of the step cycle to the next. For example, the foot angle (γ) varied sinusoidally during the transfer phase but maintained a constant value of 0° during most of the landing phase.

The motions of the different limb segments were generated according to the following general principles: The horizontal and vertical positions of the torso were varied

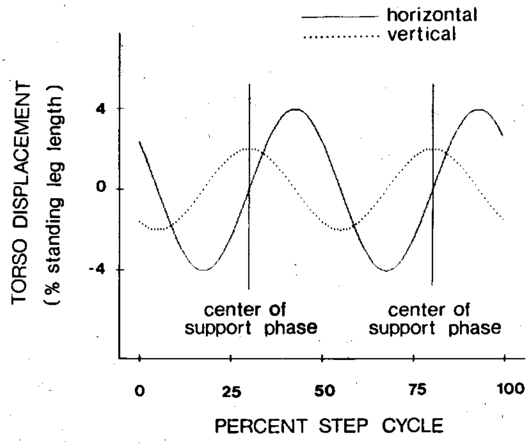

Figure 2. Changes in torso displacement relative to the ground during walking. (Zero vertical displacement equals 96% of standing leg length. Zero percent of the step cycle represents the moment when the foot first touches the ground.)

sinusoidally. The torso was at its highest point in the center of the support phase while walking, but it was at its lowest point in the center of the support phase while running. Horizontal torso displacement was 90° out of phase with the vertical torso displacement (see Figures 2 and 3). The horizontal and vertical positions of the hip relative to the torso were also varied sinusoidally. The most forward extension of the hips occurred at the beginning of the landing phase ($t = 0$) for both running and walking. The vertical hip displacement was 90° out of phase with the horizontal hip displacement (see Figure 4). During the transfer phase, the angles of the upper leg, lower leg, and foot relative to the horizontal were all varied sinusoidally. During the support phase, however, the changes in these angles were constrained by the obvious requirement that the foot remain in fixed contact with the ground. Thus, during the landing phase, the foot would continue its sinusoidal motion from the transfer phase until it achieved a value of 0°, at which time it would maintain a constant value. The foot would land on its heel while walking and on its toe while running. Given the position of the heel and hip, the position of the knee could be uniquely determined using elementary trigonometry. During the drive phase, the knee angle (δ) was varied sinusoidally. The knee angle would attain its maximum value at the beginning of the drive phase while walking and at the end of the the drive phase while running. Given the position of the toe (which was in fixed contact with the ground), the position of the hip, and the knee angle, the positions of the knee and heel could again be determined using elementary trigonometry. The resulting patterns of motion over the entire step cycle for the upper leg angle (α), lower leg angle (β), and foot angle (γ) are shown in Figures 5, 6, and 7.[1]

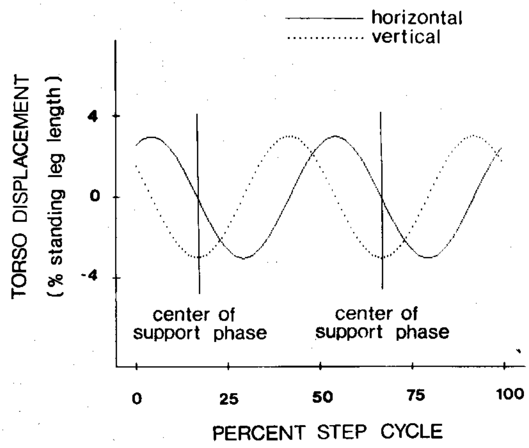

Figure 3. Changes in torso displacement relative to the ground during running. (Zero vertical displacement equals 92% of standing leg length.)

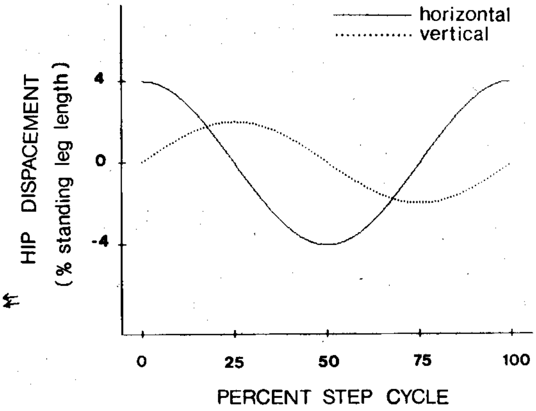

Figure 4. Changes in hip displacement relative to the torso during running and walking.

It is important to point out that the method of simulation used in these experiments was never intended to model the physical processes involved in human gait, and that the specific parameters for generating the different displays were determined by trial and error solely on the basis of perceptual criteria. Nevertheless, there are two sources of evidence to suggest that the simulations are reasonably accurate: First, all of the observers who have viewed these displays have reported that both the running and walking gaits are extremely compelling. Second, the different limb-segment functions generated by the program are remarkably similar to the functions

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[1] The general method of simulating human gait described in the present article is a natural extension of a similar method described previously by Cutting (1978a, 1978b). Cutting's program simulates arm and shoulder movements in addition to the motion of the legs and torso, but it does not take foot motion into account and can only be used to generate walking gaits.

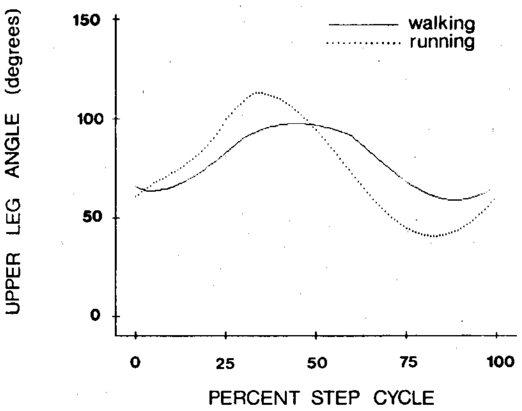

Figure 5. Changes in upper leg angle relative to the horizontal during running and walking.

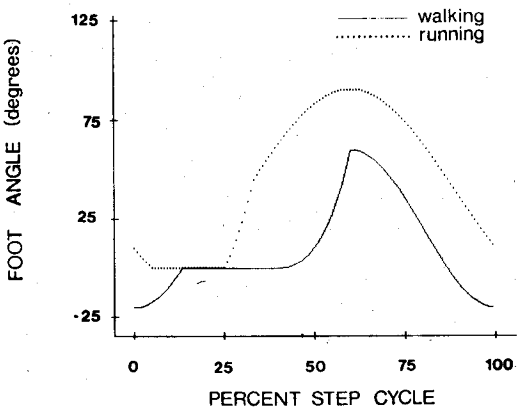

Figure 7. Changes in foot angle relative to the horizontal during running and walking.

produced by actual human subjects. This similarity is easily verified by comparing the functions in Figures 2–7 with the analogous functions for real human actors that have been published in medical literature (e.g., see Fenn, 1930; Inman, 1966; Murray, 1967; Sutherland & Hagy, 1972).

Of the seven limb-segment functions used to generate the motion of a single leg, five of those functions were significantly affected by the particular gait being simulated. These included the horizontal torso displacement, the vertical torso displacement, the upper leg angle, the lower leg angle, and the foot angle. (The horizontal and vertical hip displacements were the same for both walking and running.) The displays used in Experiment 1 were designed to determine which of these differences between running and walking provide perceptual information about an individual's gait. Thirty-two displays were constructed using all possible combinations of the different limb-segment functions for running and walking. For example, one of the displays was composed of the horizontal and vertical torso-displacement functions from walking, combined with the upper leg, lower leg, and foot angle functions for running.

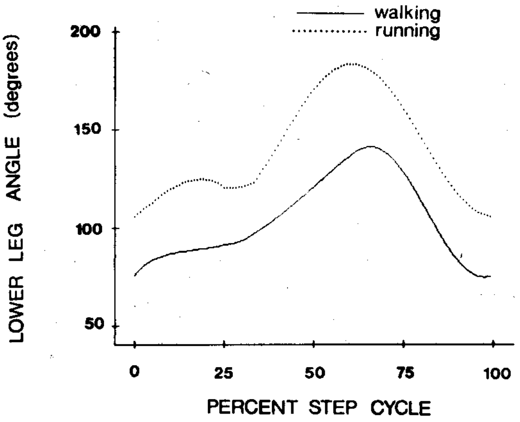

Figure 6. Changes in lower leg angle relative to the horizontal during running and walking.

Each step cycle in a given display consisted of a sequence of 120 frames presented at a rate of 52.8 frames/sec. The entire sequence was repeated several times during each trial to simulate continuous locomotion at a rate of .44 step cycles/sec. Some representative limb configurations that could be observed for different gaits at various points in the step cycle are shown in Figure 8.

Procedure. The observers participated in the experiment in groups of four. They were seated in front of the video monitor and presented with all 32 displays in a random sequence. (Each display consisted of five complete step cycles.) They were then given an answer sheet and told that they would see all of the displays a second time. They were instructed to examine carefully each display and to indicate on the answer sheet whether it looked more like a person walking or a person running. They were also instructed to judge the naturalness of the different gaits. A rating of 5 was used to indicate that a display looked exactly like a human being walking or running on a treadmill; a rating of 1 was used to indicate that the observed pattern of motion would never be produced by an actual human; and ratings of 2, 3, and 4 were used to indicate intermediate cases. Following these instructions, the observers were presented with a second random sequence of the 32 displays. In this second presentation, each display consisted of 10 complete step cycles. Two different randomizations of the stimuli (Sequences A and B) were used in the experiment. Half of the observers saw Sequence A followed by Sequence B. The remaining observers saw the sequences in reverse order.

Results

The results of the gait-identification task were amazingly consistent across observers. Out of 704 total responses, 701 corresponded to the lower leg angle function. That is, whenever a display was constructed with a walking lower leg angle function, it was perceived as walking, and whenever a display was constructed with a running lower leg angle function it was perceived as running, regardless of the motions of the other limb segments. This result suggests that the perceptual distinction between running and walking is solely determined by the motion of the lower leg.

The naturalness ratings were much more sensitive to the different experimental manipulations. This sensitivity was revealed by an analysis of variance, which measured the effects of stimulus order, gait, and function compatibility. The gait variable indicated whether the lower leg angle function of a particular display was selected from walking or running. The function compatibility variable indicated whether the motions of the other limb segments were selected from the same gait as the lower leg angle function. The analysis revealed that (a) the effect of stimulus order was negligible, $F(1, 20) = 1.743$, $p > .05$; (b) the running gaits produced higher ratings than the walking gaits, $F(1, 20) = 19.989$, $p < .001$; (c) there was a significant effect of function compatibility, $F(15, 300) = 43.836$, $p < .001$; and (d) there was a significant interaction between gait and function compatibility, $F(15, 300) = 12.099$, $p < .001$.

A more detailed breakdown of the function compatibility effect revealed that the naturalness ratings were significantly higher when the upper and lower leg motions were selected from the same gait, $F(1, 300) = 423.181$, $p < .001$. This effect accounted for over 46% of the between-display sum of squares. The ratings were also higher when the lower leg and foot motions were selected from the same gait, $F(1, 300) = 204.695$, $p < .001$, accounting for over 22% of the sum of squares. The compatibility of the vertical torso-displacement function was statistically significant, $F(1, 300) = 12.660$, $p < .001$, but this effect accounted for only 1% of the sum of squares. The compatibility effects of the horizontal torso-displacement function and the interactions between the motions of different limb segments were negligible.

The significant interaction between gait and function compatibility resulted primarily from two factors. First, the combination of a walking upper leg angle function with a running lower leg angle function was perceived as more natural than a running upper leg angle function combined with a walking lower leg angle function, $F(1, 300) = 72.502$, $p < .001$. The reason for this interaction is clearly revealed in Figure 8. In the former case (see Figure 8D), all of the resulting knee angles were anatomically possible, whereas in the latter case (see Figure 8B), some of the resulting knee angles were anatomically impossible. A second component in the significant interaction between gait and function compatibility is that the combination of a walking foot angle function with a running lower leg angle function (see Figure 8D) was perceived as less natural than a running foot angle function combined with a walking lower leg angle function (see Figure 8B), $F(1, 300) = 79.572$, $p < .001$. In this instance, the resulting ankle angles from the latter com-

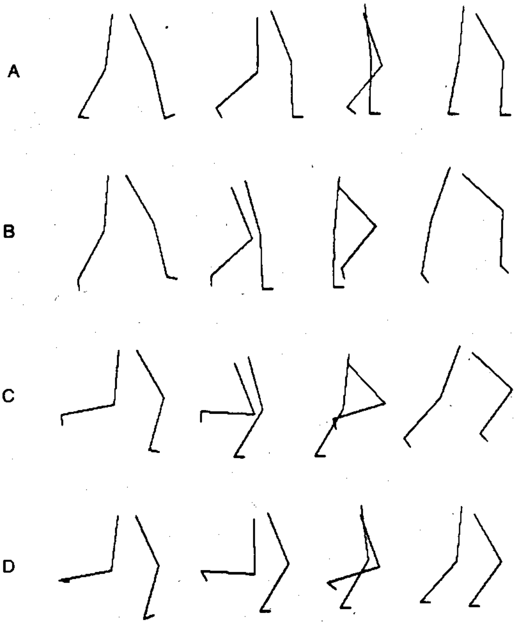

Figure 8. Static snapshots of limb configurations at different times within the step cycle for four different patterns of motion: (A) natural walking, (B) a walking lower leg angle function combined with a running upper leg and foot angle function, (C) natural running, (D) a running lower leg angle function combined with a walking upper leg and foot angle function. (The left snapshot of each row represents the moment when a foot first touches the ground. The other snapshots from left to right represent 25%, 50%, and 75% of the period until the next foot touches the ground.)

bination were all anatomically possible, whereas some of the ankle angles from the former combination were anatomically impossible. These two effects accounted for about 15% of the between-display sum of squares.

Experiment 2

Experiment 2 examined the abilities of naive observers to distinguish between running and walking and to detect unnatural limb configurations in a static image.

Method

Thirty-two static snapshots from eight of the displays used in Experiment 1 were printed out using a Tektronix video hard-copy unit. The eight displays included all possible combinations of the upper leg angle function, the lower leg angle function, and the foot angle function from running and walking. (Torso motions were ignored because the position of the torso is undetectable in a static image if the ground plane is not depicted.) Four snapshots were taken at equal intervals in the step cycle of each of the eight displays (see Figure 8).

The 32 snapshots were arranged in two random sequences and shown to 20 naive observers. Half of the observers saw one sequence; the remaining observers saw the other. The observers were instructed to look through the entire set of 32 snapshots to get a feel for the different stimuli on which their judgments would be based. They were then instructed to examine each snapshot a second time and to indicate on a separate answer sheet whether it looked more like a person walking or a person running. The observers were also required to rate the naturalness of each snapshot on a scale of 1 to 5 as in Experiment 1.

Results

The results were generally similar to those obtained in Experiment 1. Approximately 90% of the gait-identification judgments corresponded to the lower leg angle function. This correspondence is not quite as large as the one obtained for dynamic displays, but it is highly significant, $F(1,\ 18) = 479.653$, $p < .001$, accounting for nearly 95% of the between-display sum of squares.

An analysis of the naturalness ratings revealed that there was a significant effect of function compatibility, $F(3,\ 54) = 30.39$, $p < .001$, and a significant effect of position in the step cycle $F(3,\ 54) = 6.99$, $p < .001$. The effect of gait was negligible, but all of the interactions between these effects were significant at the .001 level. In contrast to the previous experiment, none of the main effects or their interactions accounted for a disproportionate percentage of the between-display sum of squares. The data do not reveal how all of these different factors are combined to determine perceived naturalness.

To compare the effects of function compatibility for Experiments 1 and 2, the mean naturalness ratings were computed for all displays that had the same number of incompatible functions. For the purpose of this analysis, a display had two incompatible functions if the upper leg and foot motions were both selected from a different gait than was the lower leg motion; a display had one incompatible function if the upper leg motion was selected from a different gait than was the foot motion; and a display had no incompatible functions if the upper leg and foot motions were both selected from the same gait as the lower leg motion. The results are presented in Figure 9. These data show clearly that generating gaits using incompatible functions has a much greater effect on

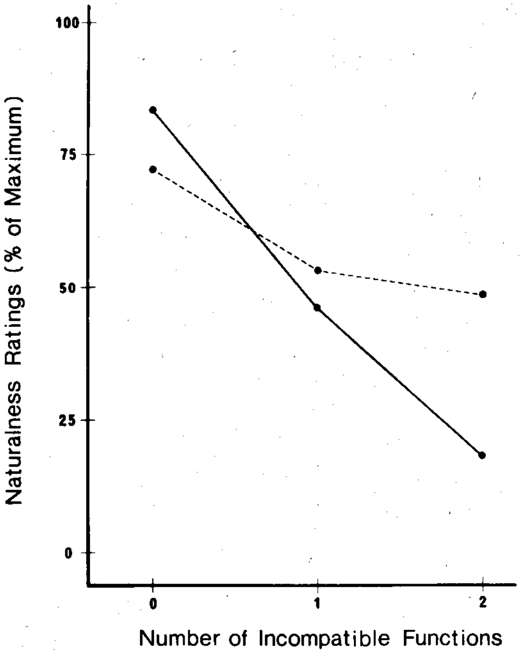

Figure 9. Naturalness ratings for moving and stationary displays as a function of the number of incompatible functions. (Solid lines represent responses to moving displays. Dotted lines represent responses to stationary displays.)

the perceived naturalness of dynamic displays than it does on the perceived naturalness of static displays.

Experiment 3

Two obvious differences exist between the lower leg angle functions for running and for walking that could conceivably be used for perceptual identification (see Figure 6). First, the functions have slightly different shapes. The running function was a small hump at the beginning of the step cycle that is not observed in the walking function. Second, the two functions are separated from one another by constant angular displacement of approximately 42°. In other words, at every point in the step cycle, the running function produces an angular displacement of the lower leg that is approximately 42° larger than the corresponding displacement produced by the walking function. In the terminology of signal theory, the mean value of a periodic function is referred to as its *d-c component*. In the absence of a formal analysis, however, it is more convenient to measure the separation between these functions by comparing their maximum values of angular displacement. (As shown in Figure 6, the maximum values are 141° for walking and 183° for running.) Taking both of these factors into account, a given lower leg angle function can be adequately characterized by two properties: its shape (running or walking), and its maximum value of angular displacement (i.e., its d-c component).

Suppose that the perceptual distinction between running and walking were primarily determined by the maximum value of angular displacement. If this were the case, it would be possible to transform a walking gait into a running gait (or vice versa) by simply adding or subtracting a constant value to the angle of the lower leg at every point within the step cycle. In other words, by systematically varying the maximum value of angular displacement, we would discover a critical value that marks the boundary between running and walking. If other factors, such as the shape of the lower leg angle function or the movements of other limb segments, could also contribute to the perceptual identity of a gait, then their respective contributions might be revealed as a shift in the position of the categorical boundary. Experiment 3 was designed as a test of these hypotheses.

Method

In constructing the displays, there were two possible shapes for the lower leg angle function (running and walking), eight possible maximum angular displacements (141° to 183° at 6° intervals), and two possible combinations of motion for the other limb segments (all running or all walking). Thus, 32 possible displays could appear on any given trial.

Eighteen naive observers participated in the experiment to fulfill the requirements of an introductory psychology class. The instructions and procedures were identical to those used in Experiment 1.

Results

Figure 10 shows the percentage of running responses as a function of maximum angular displacement for each combination of lower leg function shape and the motion of other limb segments.

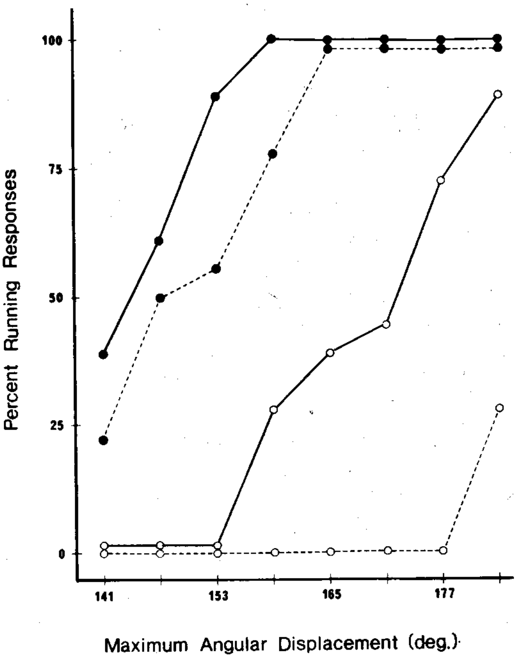

Figure 10. The percentage of running responses as a function of the maximum value of angular displacement for the lower leg. (Open circles indicate that the upper leg, torso, and foot motions were selected from a walking gait. Solid circles indicate that these motions were selected from a running gait. Dotted lines indicate a walking lower leg angle function shape. Solid lines indicate a running lower leg angle function shape.)

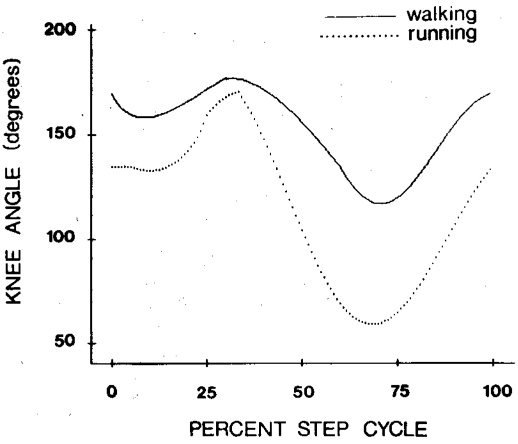

Figure 11. **Changes in knee angle during running and walking.**

An analysis of these data revealed that there was a significant effect of maximum angular displacement, $F(7, 112) = 54.236$, $p < .001$. Although the effect was dampened somewhat by obvious ceiling and floor effects, it still accounted for over 25% of the between-display sum of squares. The motion of the other limb segments also had an effect on determining gait identity, $F(1, 16) = 300.318$, $p < .001$, accounting for approximately 57% of the sum of squares. As is evident in Figure 10, the response curves were shifted to the left or right depending on whether the movements of the other limb segments were selected from walking or running. The running movements (represented by solid circles) produced a greater number of running responses, whereas the walking movements (represented by open circles) produced a greater number of walking responses. The shape of the lower leg angle function had a much smaller, though highly significant, effect on the gait-identity judgments, $F(1, 16) = 23.684$, $p < .001$, accounting for just over 6% of the sum of squares. This effect is revealed in Figure 10 by a leftward shift of the solid curves (representing the running shape) relative to the dotted curves (representing the walking shape). All of the interactions between these effects were significant at the .001 level, accounting for about 12% of the between-display sum of squares.

These results indicate that the perceptual distinction between running and walking is considerably more complex than was revealed in Experiments 1 and 2. Although identity judgments are apparently dominated by the d-c component of the lower leg angle function, they are also influenced to a lesser extent by the shape of the lower leg angle function and the movements of other limb segments.

Experiment 4

A potential difficulty in interpreting the results of these experiments is that many possible sets of variables exist that can uniquely define a given configuration of limb segments. Although the results seem to indicate that the perceptual distinction between running and walking is largely determined by the lower leg angle function, it is quite possible that observers were exploiting some other aspect of the displays that systematically covaried with the lower leg angle. One such potentially confounding variable is the knee angle (δ). In all of the displays described thus far, the knee angle was controlled indirectly by manipulating the upper and lower leg angles. The resulting patterns of change for both running and walking are shown in Figure 11. If the knee angle function had any effect on the gait-identification tasks of Experiments 1, 2, and 3, it was totally confounded with the effects of the lower leg angle function. Experiment 4 was designed, therefore, to compare the relative significance of the lower leg and knee angle functions for perceptually distinguishing running from walking.

Method

In constructing the displays, there were two possible lower leg angle functions (running and walking), two possible knee angle functions (running and walking), and two possible combinations of foot angle and torso-displacement functions (all running and all walking). Thus, eight possible displays could appear on any given trial. These displays were arranged into two random sequences of 32 trials, in which each display appeared four times. Ten naive observers participated in the experiment to fulfill the requirements of an introductory class. The instructions and procedures were identical to those used in Experiments 1 and 3.

Results

Approximately 82% of the gait-identity judgments corresponded to the lower leg angle function. This effect was highly significant, $F(1, 63) = 133.03$, $p < .001$, but it accounted for only 64% of the between-display sum of squares, as opposed to nearly 100% in Experiment 1. The effect of the knee angle function was also significant, $F(1, 63) = 45.50$, $p < .001$, accounting for 22% of the sum of squares, and there was a small effect of the other limb-segment motions, $F(1, 63) = 9.51$, $p < .005$, which accounted for about 5% of the sum of squares. These findings indicate that the knee angle function can exert a major influence on the perceptual identity of a gait independently of the lower leg angle function.

Discussion

During the past decade there has been a growing amount of research on how human observers perceive biological motion. It has been shown, for example, that the relative movements of a few spots of light can provide perceptually salient information about distinct gaits such as running or walking (Johansson, 1973, 1975, 1976; Hoenkamp, 1978), the identity of a friend (Cutting & Kozlowski, 1977), an individual's gender (Barclay et al., 1978; Cutting, 1978a; Cutting et al., 1978; Kozlowski & Cutting, 1977), or the amount of force that is exerted when a person lifts a heavy weight (Runeson & Frykholm, 1981). These experiments have demonstrated convincingly that observers can identify complex configurations of motion under extremely impoverished viewing conditions, but they have not revealed the specific properties of a moving display that make one configuration distinct from another. The research reported in the present article has attempted to address one small aspect of this general problem. That is, it has examined some specific properties of a moving configuration of limb segments that can influence the perceptual distinction between human running and walking.

Before considering the theoretical implications of this research, it is useful to compare the results and procedures with a similar investigation reported by Hoenkamp (1978). As in the present study, Hoenkamp used a computer-animation technique that allowed him to manipulate the motion of each limb segment independently. His displays consisted of just five points that were intended to depict the hip, knees, and ankles of a human actor. The hip was represented by a fixed point in the center of the display screen, the two upper leg angles were controlled by sine functions varying in counterphase, and the two lower leg angles were controlled by sawtooth functions varying in counterphase. On the basis of his own observations, Hoenkamp concluded that the most important stimulus parameter for distinguishing running from walking is the proportion of the step cycle in which the lower leg segment moves backward. (His optimal running and walking displays had proportions of .6 and .85, respectively.) These observations are difficult to interpret, however, because he also reported a strong tendency to perceive the displays as the relative motions of the head, wrists, and ankles rather than of the hip, knees, and ankles as was originally intended.

Although the methodology used in the present experiments was closely related to Hoenkamp's methodology in many respects, there were two fundamental improvements in how the displays were generated. First, the simulations were considerably more accurate. They incorporated the motions of the torso, hips, and feet in addition to the upper and lower legs, and the motions of the different limb segments were not restricted to simple sine or sawtooth functions. The functions depicted in Figures 2–7 were all carefully matched to the limb movements produced by actual human actors. The functions were also coordinated so that the feet would remain in fixed contact with the ground during their respective support phases. This would not have been possible with the simpler functions used by Hoenkamp (1978) or Cutting (1978b). A second important property of the displays used in the present experiments is that they were composed of connected line segments rather than isolated points of light. When leg movements were simulated by Hoenkamp using point-light displays, the observers were unable to determine the connectivity relations between the individual display elements.[2] In other words,

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[2] The endpoints of this perceived-naturalness scale should not be interpreted too literally. There is no reason to believe that the displays rated most natural are the best possible depictions of a human gait that could be generated in principle. Nor should one conclude that the

the observers' identity judgments were based on a perceived configuration of motion that was different from the actual pattern of limb movements used to generate the displays. The problem is easily avoided, however, by connecting the elements of a display with visible line segments. This solution provides perceptually salient information about connectivity relations (see Figure 8), so that the process of gait identification can be performed on a clearly defined configuration of limb segments.

After devising an appropriate method of simulating human gaits, Experiment 1 was designed to discover the specific properties of those simulations that perceptually distinguish running from walking. Thirty-two displays were generated in a 2 × 2 × 2 × 2 × 2 factorial design to assess how the perceived identity and naturalness of a gait are affected by vertical torso motion, horizontal torso motion, upper leg motion, lower leg motion, and foot motion. The naturalness judgments revealed that the observers were particularly sensitive to the relative motions of the upper leg, lower leg, and foot. When all of these limb-segment motions were selected from the same gait, the displays were given the highest possible naturalness ratings; when they were all selected from different gaits, the displays were given the lowest possible naturalness ratings (see Figure 9).[3] However, although the observers were clearly sensitive to the relative motions of the different limb segments, their identity judgments were determined almost exclusively by the motion of the lower leg. The magnitude of this effect was quite surprising, accounting for over 99.57% of the individual responses. Even the displays that were judged to be unnatural were reliably identified as running or walking by all 22 observers. This latter observation is especially interesting because it suggests that the perceived identity and naturalness of a gait are determined by different principles.

Experiment 2 examined the abilities of naive observers to distinguish between running and walking and to detect unnatural limb configurations in a static image. The results showed clearly that motion is not a necessary condition for the perception of gait. All of the observers could reliably identify running or walking from a single static snapshot composed of only six line segments. Indeed, the results were similar to those obtained in Experiment 1 in that most of the gait-identity judgments were determined by the orientations of the lower legs. This finding highlights the methodological advantages of using displays composed of connected line segments for studying the process of gait perception. When a stationary depiction of a human actor is presented in the form of a point-light display, it is inevitably perceived as a random configuration of disconnected elements. This failure to perceive the actual structure of the display says nothing about the process of gait identification, however, since it results from the observer's inability to determine the connectivity relations between the individual display elements. Of course this does not suggest that motion is irrelevant to the perception of gait when a display is composed of connected line segments. One important difference that distinguished the pattern of responses to moving and stationary displays in the present experiments is that the observers seemed to have difficulty judging the naturalness of a stationary configuration of limb segments. Whereas the compatibility of the different limb-segment functions accounted for 67% of the between-display sum of squares for the moving displays, it accounted for only 15% of the sum of squares for the stationary displays (see Figure 9). This result supports the conclusion of Experiment 1 that judging the

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displays rated least natural are the worst possible depictions of a human gait. For example, although the pattern of motion depicted in Figure 8(B) was generally rated as maximally unnatural, it was always recognized as a human gait. The overwhelming majority of motion configurations that could be generated with six connected line segments would be perceived as nothing more than random gyrations.

[3] A similar phenomenon was observed in a pilot version of the present experiments. When only the endpoints of the different limb segments were displayed, the knee elements were perceived as if they were attached to the wrists, and the hip elements were perceived as if they were attached to the head. Gait identity and naturalness judgments under these conditions were extremely unreliable.

naturalness of a gait is a more complicated process than determining its identity.

In Experiment 3 a more fine-grained manipulation of the lower leg angle function was performed in order to determine how specific properties of its structure affect the perceptual distinction between running and walking. The results demonstrated that a perceptually salient walking gait can be transformed into running (or vice versa) by adding or subtracting a constant value to the angle of the lower leg over the entire step cycle. In other words, by gradually manipulating the d-c component of the lower leg angle function, it is possible to map out a well-defined boundary that separates the perceptual categories of human running and walking. This procedure is considerably more powerful than the one used in Experiments 1 and 2. Although the earlier findings had suggested that the perceptual distinction between running and walking is solely determined by the orientations of the lower legs, the significant effects of the other limb-segment functions were clearly revealed in Experiment 3 by appropriate shifts in the categorical boundary (see Figure 10).

To evaluate the results of the present experiments, it is important to remember that a large number of covariant measures can be defined for a configuration of limb segments. The lower leg angle, for example, is covariant with the vertical distance from the ankle to the ground and the orientation of the line connecting the two toes. The methodological implications of having many covariant descriptions of a human gait are clearly demonstrated by the contrasting results of Experiments 1 and 4. In Experiment 1 a configuration of limb segments was uniquely defined in terms of hip position, upper leg angle, lower leg angle, and foot angle (see Figure 1). When the changes in these variables were mixed together in all possible combinations in a gait-identity task, the lower leg angle accounted for virtually 100% of the between-display sum of squares. In Experiment 4, the displays were defined using a different set of variables in which the upper leg angle was replaced by the knee angle. When the changes in these variables were mixed together in all possible combinations, the lower leg angle accounted for only 64% of the between-display sum of squares. The effect of the knee angle was apparently masked in Experiment 1 because of the particular choice of variables for generating the displays. This problem of covariant descriptions is an endemic property of all research on human gait perception, since there are many more potential variables in a configuration of limb segments than could conceivably be examined within a reasonable number of experiments. Thus, although the present research has provided strong evidence that the perceptual distinction between running and walking is largely determined by the orientations of the lower leg, it is best to view this conclusion with a certain degree of circumspection.

Many other aspects of human gait perception remain to be examined by future research. One relevant issue is the extent to which upper body movements can influence the perceived identity and naturalness of a gait. The movements of the arms while running or walking are much less stereotyped than the movements of the legs. When an individual is walking, for example, the arms may be gently swaying in counterphase to the legs; they may be waving high in the air, held tightly across the chest or engaged in playing a musical instrument. Nevertheless, reliable differences exist between the upper body movements for different gaits that could provide an observer with usable information (e.g., the churning of the arms during a sprint is quite distinct from the gentle swaying of the arms that typically occurs while walking). Another relevant issue for future research is to consider a broader spectrum of biological motion besides human running and walking. Even within the restricted domain of human gait, there are a wide variety of perceptually distinct categories including running, walking, marching, skipping, jumping, hopping, and limping. It is also possible to perceive many subtle variations within each category (e.g., an individual's walk could be graceful, plodding, swaggering, or seductive). Our current knowledge of the specific information on which these distinctions are based is extremely limited.

One important factor that makes studying these issues especially difficult is the enormous complexity of the necessary stimulus displays. Indeed, it is not even clear how different variations of human gaits could be adequately described without plotting all of the possible trajectories for each individual limb segment. Although several attempts have been made in recent years to provide formal mathematical descriptions for complex configurations of motion (e.g., Cutting, 1981; Johansson, 1976; Restle, 1979; Todd, 1982), none of these methods are sufficiently powerful to capture the perceptual distinctions among human gaits. Cutting's (1981) analysis of point-light walkers, for example, would produce an identical description for every display used in the present experiments. One possible approach to this problem is to use the technique of Fourier analysis. The feasibility of this approach for the study of human perception was nicely demonstrated in a recent pilot experiment performed by Johansson and Bäckström (Note 1). They carried out a Fourier analysis of the forced pendular motions of the hip, knee, shoulder, and elbow joints of a human walker, and constructed artificial gait patterns by means of a Fourier synthesis. When only the fundamental frequencies were incorporated in the displays, the observers perceived a rather unreal, "floating" type of gait. The displays started to look more natural when the synthesis included the second and third harmonics, but the perception of "force" in a gait was not restored until even higher harmonics were added. These observations provide a sobering indication of the complexity required for an adequate description of human gait; a Fourier analysis carried out to five harmonics for an arbitrary configuration of eight points would involve 192 independent parameters.

Reference Note

1. Johansson, G. & Bäckström, L. Personal communication, March 29, 1982.

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