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Visual Control of Step Length During Running Over Irregular Terrain

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Running over uneven ground requires visually regulating step length to secure proper footing. To examine how this is achieved, we studied subjects running on a treadmill on a series of irregularly spaced targets. The movements of their lower limbs and coccyx relative to the targets were monitored opto-electronically by a Selspot system. The results indicated that step length was adjusted to strike the targets primarily by varying the vertical component of impulse applied to the ground during the stance phase. In contrast, horizontal impulse was not varied significantly, and changing the reach forward of the foot on landing contributed little to variation in step length. Changing the vertical impulse simply altered the step time proportionately. Thus the data are consistent with a time-based model in which vertical impulse is modulated by the optic variable $\Delta\tau$ (Lee, 1976) specifying the time gap that has to be bridged by the runner between two targets.

The gait patterns of humans and other vertebrates have been closely studied in a variety of species and at various speeds of locomotion (Arshavsky, Kots, Orlovsky, Rodinov, & Shik, 1965; Goslow, Reinking, & Stuart, 1973; Grillner, Halbertsma, Nilsson, & Thorstensson, 1979; Herman, Wirta, Bampton, & Finley, 1976; Shapiro, Zernicke, Gregor, & Diestel, 1981; see Grillner, 1975, and Shik & Orlovsky, 1976, for reviews). However, in the interest of identifying the basic or "stereotypic" features of gait, nearly all such studies have been conducted on flat, homogeneous surfaces such as a treadmill or prepared track. In contrast, it is apparent that the locomotor system evolved for moving over irregular terrain, cluttered with obstacles and uneven surfaces of varying compliance. Research in this area has concentrated on proprioceptive reflexes and postural mechanisms that might serve to return the body to balance after it has been disturbed by a mechanical perturbation (Forssberg, Grillner, & Rossignol, 1975, 1977; Nashner, 1980; Orlovsky & Shik, 1965). Such perturbations can occur, for example, if the foot strikes irregular ground in the wrong way or hits an obstacle. Prevention is better than cure, however. Most of the time, perturbations are simply avoided by looking at the ground ahead and adjusting gait to match the terrain. How this is done has received relatively little study (Turvey & Remez, 1979). In this paper, we examine the visual adjustment of step length during running on an irregular ground surface.

Recent approaches to the problem of motor coordination and control stress the organization of muscles into functional task-specific groupings called *synergies* or *coordinative structures*, which establish a particular pattern of activation of the musculature (Bernstein, 1967; Easton, 1972; Gelfand, Gurfinkel, Tsetlin, & Shik, 1971; Turvey, 1977). This autonomous organization serves to reduce the dimensionality or number of degrees of freedom of the motor system down to a few parameters, which can be controlled in order to adjust the overall pattern. In the case of locomotion, for example, Shik & Orlovsky (1976) proposed that a spinal automatism establishes the basic sequence of joint movements and muscle activity in the dog, with different speeds of locomotion produced by varying only the "propulsive force" developed during the stance phase; all other changes in the step cycle are a biomechanical consequence of variations in this parameter (Arshavsky et al., 1965; Orlovsky, Severin, & Shik, 1966). Contrasting approaches to such motor organization have been offered either by ascribing the sequence and timing of movement to a preexisting motor program or central pattern generator (Keele, 1973; Pearson, 1972; Schmidt, 1975; Shapiro et al., 1981; Selverston, 1980) or by treating them as a consequence of the properties of a self-organizing dynamical system (Kugler, Kelso, & Turvey, 1980, 1982; Kelso, Holt, Rubin, & Kugler, 1981).

Given that task-specific constraints arise within the motor system, leaving only a few parameters free to vary, movement may be visually adapted to environmental conditions by allowing these motor parameters to be modulated by variables of optical stimulation. Spatiotemporal patterns of change in the optic array, as described by Gibson (1966, 1979) and Lee (1974), provide information about both the layout of the environment and the motion of the observer through it. Such patterns may directly control not only the timing of motor acts (Lee, 1976, 1980) but also the "propulsive forces" required to yield accurate movements (see Fitch & Turvey, 1978; Lee, Lishman, & Thomson, 1982; Warren & Kelso, 1985). This raises the problem of how the *kinetic* force-related variables of action might be regulated by the merely *kinematic* or spatiotemporal variables of the optic array. Experiments on the visual control of movement could thus seek to determine (a) the action parame-

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ter that varies in adapting a movement to changing environmental conditions, (b) the optical variable that acts to modulate this parameter, and (c) the function that relates them. In the present study, we seek to determine the parameters of human gait that are varied in order to adjust step length to irregular terrain; a subsequent report will examine the timing of visual information pickup necessary for the successful control of these parameters. The first step is to describe the nature of the control problem.

Ways of Changing Step Length

A necessary condition for running over a level surface is maintaining balance. This must be done while following a course, controlling speed, and, ideally, using the minimum amount of energy. When the surface is uneven or provides intermittent footing, there is the further problem of regulating step length so as to place the feet on points of solid support. Regulating step length is, however, not independent of maintaining balance, because even apart from the balance problems that will result from a poor footing, changing foot placement relative to the body will affect the torques which must be applied if the runner is to remain stable. Foot placement and choice of course are also tied together in most real situations, because veering slightly might take the runner onto better surfaces of support. Energy efficiency, too, will be affected by the runner choosing nonoptimal step lengths.

The problem we address here is how runners control step length while maintaining balance. We begin by outlining four hypotheses about how step length might be adjusted: (a) by changing reach at heelstrike, (b) by changing forward speed, (c) by changing the vertical impulse during stance, and (d) by delaying or advancing heelstrike.

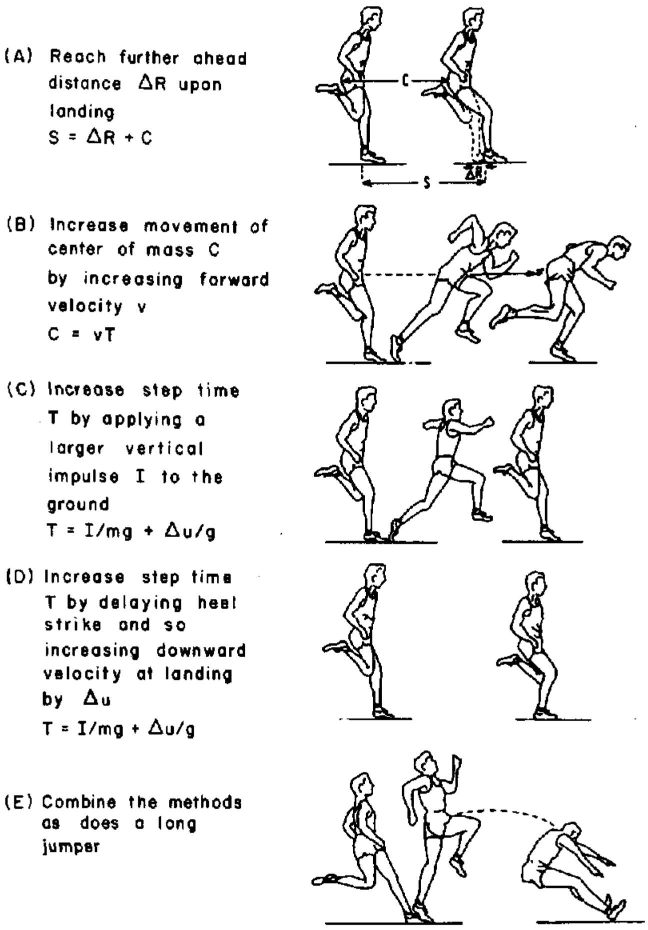

Figure 1. Ways of increasing step length. See text for explanation of the equations.

Method A: Changing Reach

Step length can be adjusted by making a change ΔR in the forward reach of the foot at heel strike, as in Figure 1, Panel A. However, this method of step length control may interact with forward–backward balance control as follows. Broadly speaking, the condition for maintaining balance is that, on average over time, the center of mass of the body should be above the point of support (Raibert et al., 1983). Thus if at a heelstrike the foot is further forward of the center of mass than normal, later compensation will be necessary, either by stretching out the leg further than normal behind the body during take-off from the same step or by reducing the reach on a subsequent step. Such adjustments can also be achieved by varying the timing of application of vertical forces during the contact period, but this does not affect the main point that adjusting the reach at heelstrike will alter the rate of overall forward–backward rotation of the runner's body and thus necessitate subsequent correction. This compensation may have two consequences: It may make it difficult to make a subsequent step of the right length to hit a target, or it may result in loss of energy efficiency, for instance, by making the run too jerky. Stretching out or tucking back the lead leg during the flight phase of the running cycle to reach for a target may, therefore, be a poor method of regulating gait.

The other way a runner can alter step length is by varying the distance traveled by the center of mass between successive heelstrikes. These two methods are illustrated in Figure 1, Panel A, and are represented by the equation

$$S = \Delta R + C, \tag{1}$$

where S is the step length measured from one heelstrike point to the next, ΔR is the reach of the second heelstrike minus that of the first, and C is the horizontal distance traveled by the center of mass between the heelstrikes. We next examine how C might be adjusted.

Method B: Changing Speed

The distance, C, traveled by the center of mass in the interval, T, between heelstrikes (the step time) is the product of T and the mean horizontal velocity, v, of the body during the step, that is,

$$C = vT. \tag{2}$$

Thus C can be regulated by changing v and/or T.

We first consider adjusting v (Figure 1, Panel B). This would require changing the horizontal component of impulse applied to the ground during stance. As a side effect, that would produce a torque about the center of mass which would need to be compensated to avoid imbalance. Thus runners lean forward when speeding up and lean backward when slowing down. In short, significantly changing v could require substantial changes in the overall pattern of running, and this would likely be inefficient.

Alternatively, there are two ways of varying step time, which we now consider.

Method C: Changing Vertical Impulse

Step time can be lengthened by applying a larger vertical component of impulse to the ground during stance, because by kicking off harder, the body is launched higher into the air (Figure 1, Panel C). If the downward momentum of the body at heelstrike, which roughly corresponds to the jolt experienced from the ground, is the same at the beginning and end of the step, then step time will be directly proportional to vertical impulse. This follows from conservation of momentum: The time integral of the vertical forces acting on the body between heelstrikes is equal to the change in vertical momentum of the body, which in this case is zero. Thus

$$mgT - I = 0$$

or

$$T = I/mg, \tag{3}$$

where T is the step time, I is the vertically upward contact impulse (i.e., the vertical component of the ground reaction force integrated over the stance period), m is the runner's mass, and g is the absolute value of the acceleration due to gravity.

The vertical impulse I can be adjusted by altering the magnitude of the force exerted on the ground during contact, and/or by changing the time over which the force is applied. The contact period starts with the center of mass behind the supporting foot and ends with it ahead of the foot. Therefore, the extra vertical impulse needed to produce a step time adjustment can, in principle at least, be distributed around the midpoint of the stance phase, so as to produce no net torque on the runner and hence no perturbation of balance. This is in contrast with Method B (Figure 1, Panel B), in which a net horizontal impulse will always produce a torque that requires compensation. Hence vertical impulse is likely to be an efficient way of varying step length.

Method D: Delaying or Advancing Heelstrike

The other way of lengthening step time is by delaying heelstrike (Figure 1, Panel D). This will result in a greater jolt from the ground, because the body will be falling for longer and so will gain more downward velocity. Suppose the delay in heelstrike results in the downward velocity at heelstrike being Δu greater than that at the preceding heelstrike. Then, in this general case, the conservation of momentum equation is

$$mgT - I = m\Delta u.$$

Thus

$$T = I/mg + \Delta u/g. \tag{4}$$

The step time could also be shortened by advancing heelstrike, in which case Δu will be negative. The runner cannot, however, make an arbitrary series of such adjustments. For example, heelstrike cannot be continually delayed, or delayed too much, without driving the runner into the ground (as in Figure 1, Panel E). In general, any delay in heelstrike must soon be compensated by advancing heelstrike (and vice versa) if the runner is to maintain an efficient gait and keep balance. The method is, therefore, suitable for changing one or two steps, as, for instance, when long jumping (Figure 1, Panel E), but when steps need to be regulated in close succession, the method is limited.

The present study examines running at a constant, submaximal speed on a *series* of targets to simulate locomotion over a heterogeneous ground surface. The irregular distribution of patches of clear ground that afford solid footing when running on a field, woodland, or hillside was simulated in one dimension by a series of irregularly spaced targets; the spaces between targets thus simulated obstacles or areas of poor footing. By examining the relations between step length and the gait variables—reach change (ΔR), center of mass movement (C), horizontal velocity of center of mass (v), step time (T), vertical impulse (I) and vertical momentum change ($m\Delta u$)—we inferred the relative contributions of these gait variables to the adjustment of step length.

Method

Subjects

Two experienced male long-distance runners, Subjects DW and DL, participated in the experiment. Subject DW had also been a competitive fell runner, a cross-country sport that involves running down rough hillsides.

Apparatus

The subject, attached to a safety harness, ran indoors on a motor-driven treadmill 1.95 m long by 1.06 m wide. Three parallel mauve nylon tapes, each 2 cm wide, were looped around the treadmill belt close to its center and ran over gray plywood sheets to pulleys 5 m in front of the treadmill (see Figure 2). The tape loops turned with the treadmill and had a Mobius half-twist in them, doubling their effective surface length to about 28 m. Yellow targets were attached to the tapes at irregular intervals in blocks of five; the targets were 2 cm wide by 30 cm long, equal to the length of the runner's shoe. Only two tapes were used in the experiment—a practice tape and a test tape (the third tape was covered up). Two blocks of targets appeared on each of the two tapes, with a blank stretch of about 9.4 m between them. Thus in total there were four different blocks of targets. For the test tape, the intervals between the leading edges of the five targets in a block were 100, 120, 140, and 160 cm; for the practice tape the intervals were 110, 130, 150, and 170 cm. These intervals appeared in a different random order in each block.

The runner's task was to run on the targets as accurately as possible, analogous to running on clear patches of ground; between the blocks he could run freely. He was instructed to stay even with a mark that was

50 cm back from the front of the treadmill belt. Only one tape was visible in front of the runner on any trial, the others being covered by gray plastic U-channel in front of the treadmill. All tapes were necessarily exposed on the treadmill belt itself, but most of this was out of the runner's view.

The movements of the runner's lower limbs were recorded with a Selspot movement measuring system interfaced to a computer. Nine infrared light-emitting diodes (LEDs) were attached to the lower limbs over the knee joint, ankle joint, heel and toe of each leg, and on a mount 5 cm posterior to the coccyx. The Selspot system provided a record of the movement as if a film of the runner had been shot at 312.5 frames/second, and then the positions of the LEDs in each frame of the film digitized on a 1,024 × 1,024 grid, to yield a sequence of (x, y) coordinate pairs. The Selspot camera was placed to the side of the treadmill 4 m from the middle of the belt, at a height of 17 cm. An emitting and receiving photocell was mounted over the test tapes at the edge of the treadmill to detect each target and permit calculation of treadmill speed and target position at heelstrike, with an accuracy of approximately 1 cm. Calibration of the Selspot system for absolute distance along the treadmill belt was performed using an LED at the beginning of each experimental session.

Experimental Procedure

The treadmill belt speed was set to approximately 4 m/s and remained constant throughout an experimental session. A subject began with 10 min of warm-up free running on the treadmill in order to induce a stable gait and encourage normal, energy-efficient adjustments of step length. A short practice period followed using the practice tape, in which the runner was instructed to run on the blocks of targets until a criterion of four successive blocks of accurate running was achieved, as judged by the eye of the experimenter. Finally, the test tape was uncovered, and the runner was instructed to run on the targets for a period that included four blocks of practice followed immediately by 10 consecutive blocks of recorded data. Each subject was thus recorded running over 50 targets.

Calculating Parameters of Gait

The camera output was digitized and stored on disk for subsequent analysis. A computer program determined the times at which heelstrike occurred, and hence the step time T for each step. The horizontal coordinate of heel position at heelstrike was measured in a frame of reference fixed in the laboratory, and hence to obtain the step length S in the treadmill frame of reference the treadmill speed was multiplied by the step time and added to the difference between successive heelstrike positions. The reach for each step was calculated as the difference between the horizontal coordinates of the coccyx and heel LEDs, and the reach change ΔR was found by subtracting successive values of the reach. The coccyx movement C was obtained by subtracting ΔR from S (Equation 1). The mean horizontal velocity of the coccyx v was found by dividing coccyx movement C by step time T (Equation 2). The vertical component of the velocity of the runner's center of mass, u, was estimated at each heelstrike from the motion of the coccyx LED, by smoothing its vertical coordinate with a Gaussian low-pass filter and differentiating. Hence the scaled vertical momentum change $\Delta u/g$ was obtained, and the scaled vertical impulse I/mg was calculated by subtraction from T (Equation 4).

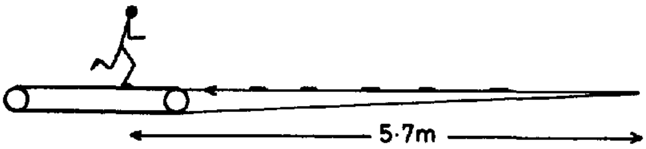

Figure 2. Experimental layout. The extension shown to the right of the treadmill belt is nylon tape carrying the yellow targets on which the subject is about to run.

The use of the coccyx LED instead of the true center of mass requires justification. The problem is that finding the position of the center of mass requires estimating the full distribution in space of all the mass of the body, and this procedure would introduce random noise, even though in principle the result would be more exact. The coccyx position does, however, provide an adequate estimate for our analysis. First, a constant offset from the center of mass produces no effect on any of the variables measured, so error is introduced only by changes in the relative positions of the coccyx and center of mass. Second, the coccyx LED is fixed relative to the most massive segment of the body, the trunk, so substantial changes in its position relative to the center of mass will demand gross changes in the positions of the runner's limbs. Because measurements were all made at the same stage of the gait cycle, heelstrike, the limbs were roughly in the same configuration for each measurement. In other words, stretching the leg out to increase the reach will move the center of mass forward relative to the coccyx LED, but the effect of this on the measured values of C and ΔR will be much smaller than the true changes in C and ΔR, and so will not distort the results. Finally, the vertical momentum estimates derived from the coccyx movement can be checked by seeing whether they are consistent with the free-fall trajectory of the center of mass during the flight phase of the steps; the results of this independent test, which is described more fully in the Results section, confirm the validity of using the coccyx LED.

For analysis, the steps were divided into two groups: For each block of targets, *run-up steps* were the six steps culminating in the heelstrike on the first target of the block; *target steps* were the succeeding four steps which involved taking off from one target and landing on the next. For each subject, 60 run-up steps and 40 target steps were analyzed. For analyses involving the coccyx position or velocity some steps had to be omitted, when the runner's hand had obscured the coccyx LED.

Results

Mean absolute error, calculated as the distance between the heel and the rear edge of the target at heelstrike, was 12.2 cm (SD = 8.3 cm) for Subject DW and 31.3 cm (SD = 18.5 cm) for Subject DL. An error less than 30 cm indicates that some portion of the foot landed on the target. Thus the task was a difficult one, but the subjects were reasonably successful in adjusting step length to land on the targets.

We will examine the relative contributions of the different gait parameters to adjustments in step length in the order set out in the introduction.

A. Reach Versus Coccyx Movement

Equation 1 states $S = C + \Delta R$, where S is the step length, C is coccyx movement, and ΔR is change in reach.

A measure of the proportionate contribution of C to the adjustment in step length is the linear regression coefficient m_C of C on S. Likewise, $m_{\Delta R}$, the linear regression coefficient of ΔR on S is a measure of the proportionate contribution of ΔR to step length adjustment. This may be seen intuitively by considering the regression equations

Table 1
Relative Contributions of Change in Reach (ΔR) and Coccyx Movement (C) to Adjustments in Step Length (S)

	Contributions to variance in S		Correlations	
Subject/steps	m_C	$m_{\Delta R}$	$r(S, C)$	$r(S, \Delta R)$
DW/run up	0.95	0.05	.94	.13
DW/on targets	0.94	0.06	.91	.14
DL/run up	0.85	0.15	.77	.22
DL/on targets	0.88	0.12	.94	.36

$$c = m_C s$$

$$\Delta r = m_{\Delta R} s,$$

where c, Δr, and s denote deviations (or adjustments) of C, ΔR, and S from their respective means. Thus

$$m_C = \text{adjustment to } C/\text{adjustment to } S$$

$$m_{\Delta R} = \text{adjustment to } \Delta R/\text{adjustment to } S,$$

where $m_C + m_{\Delta R} = 1$ (for more details see Appendix).

Table 1 shows that the reach played a very small role in controlling step length, on average accounting for less than 10% of the variance in step length. Thus although reach may perhaps be used for "fine tuning" the length of a step at the last moment, most of the adjustment is done without making this change to the body's geometry at heelstrike.

B. Speed Versus Step Time

Coccyx movement C is the product of mean horizontal velocity v and step time T, as in Equation 2:

$$C = vT.$$

The equation can be written

$$\log C = \log v + \log T,$$

and the analysis of Section A above applied to the logarithms. (Working in Edinburgh, we naturally chose Napierian logarithms, but common logarithms could also have been used.)

Table 2 shows that variations in the forward velocity hardly contributed at all to changes in coccyx movement on each step: The body of the runner kept moving forward steadily, and the step length was controlled by changing the step time. This has important consequences not only for biomechanical efficiency, but also for the nature of the information required by the locomotor system, as will be considered further in the Discussion.

C. Timing of Heelstrike Versus Vertical Impulse

The step time T may be controlled by changing vertical impulse I during stance and/or by a change in vertical velocity Δu at heelstrike brought about by changing the timing of heelstrike as given by Equation 4:

$$T = I/mg + \Delta u/g.$$

Table 2
Relative Contributions of Forward Velocity (v) and Step Time (T) to Adjustments in Coccyx Movement (C)

	Contributions to variance in $\log C$		Correlations	
Subject/steps	$m_{\log C}$	$m_{\log v}$	$r(\log C, \log T)$	$r(\log C, \log v)$
DW/run up	0.92	0.08	.99	.50
DW/on targets	0.99	0.01	.99	.07
DL/run up	1.06	−0.06	.96	−.17
DL/on targets	0.99	0.01	.98	.02

Applying the above linear regression analysis, once again one variable was found to be dominant: The vertical impulse accounted for almost the whole of the change in step time (Table 3).

As the estimate of the impulse was carried out indirectly, this result was checked by applying conservation of momentum to the flight phase of the steps. During flight there is no ground contact impulse, so $T_f = \Delta u_f/g$, where T_f is the flight time and Δu_f is the change in the downward component of the velocity of the center of mass from the toe-off at the start of flight to the heelstrike at the end of flight. We obtained Δu_f, like Δu, from the coccyx LED velocity, to test whether our estimates obeyed this equation. To a good approximation, they did: $\Delta u_f/g$ accounted for on average 90% of the variation in T_f. This indicates that the results for the whole step times are reliable and that the bulk of the variation in step time is indeed due to the variation in vertical impulse.

Discussion

In sum, we conclude that step length was adjusted to land on the targets primarily by varying a single gait parameter, the vertical component of impulse applied during the stance phase. This alters step time and, consequently, the distance traveled during the step. In contrast, horizontal impulse was not regulated at all, and reach change made a relatively minor contribution, though it may be important as a final precise adjustment. This is consistent with the results of Lee et al. (1982), which indicated that for long jumpers sprinting to the take-off board

Table 3
Relative Contributions of Scaled Vertical Impulse (I/mg) and Scaled Vertical Velocity Change ($\Delta u/g$) to Step Time (T)

	Contributions to variance in T		Correlations	
Subject/steps	$m_{I/mg}$	$m_{\Delta u/g}$	$r(T, I/mg)$	$r(T, \Delta u/g)$
DW/run up	0.97	0.03	.82	.04
DW/on targets	1.09	−0.09	.75	−.09
DL/run up	0.81	0.19	.79	.29
DL/on targets	1.01	−0.01	.66	−.01

vertical impulse was used to adjust the last several steps of the approach to the board.[1] Apparently, the high dimensionality of the motor system is internally constrained for running in such a way that the control of a single parameter yields an appropriate step length.

What visual information might a runner use to control vertical impulse? If it were information about distance between targets, then the runner would also need information about his or her speed, because the impulse required to bridge two targets depends both on their separation and the running speed. More simply, vertical impulse could be modulated by the optic variable tau, which specifies the time-to-contact under constant velocity of an approaching object with the plane through the observer's eye perpendicular to the direction of approach (Lee, 1974, 1980; Lee & Young, 1985). When approaching an object on the ground at constant speed, tau specifies the time-to-contact with the feet. For two approaching targets, the difference between their values of tau is the tau gap ($\Delta\tau = \tau_2 - \tau_1$), which specifies the temporal duration of the step needed to take off from the first target and land on the second. The runner could monitor the tau gap as he or she was landing on the first target of the pair, and apply a vertical impulse that would yield a step time equal to the specified tau gap. Given a proportionate relation between vertical impulse and step time (as shown in the experiments reported here), an accurate step length would be an automatic consequence of controlling impulse with $\Delta\tau$.

Formally, our model is that the required vertical impulse is specified to the runner by the control function

$$I = mg\Delta\tau, \qquad (5)$$

which is obtained by substituting the optic variable $\Delta\tau$ for the variable T in Equation 4 (with Δu omitted because it was found to be negligible). Thus we hypothesize that the "known" kinetic variable of body mass scales the optic variable $\Delta\tau$ to the action parameter I.

The advantage of a model based on time rather than distance is that vertical impulse is proportional to $\Delta\tau$ regardless of speed. Furthermore, there is evidence that the variable τ is utilized to control the onset timing of motor acts in a variety of species, including the initiation of wing folding in diving sea birds (Lee & Reddish, 1981), landing deceleration in insects (Wagner, 1982), leg extension in ski-jumping (Lee, Lishman, & Thomson, 1982), and leg and arm extension in leaping to hit a ball (Lee, Young, Reddish, Lough, & Clayton, 1983). The model proposed here follows the suggestion made by Lee et al. (1982) that τ is used to regulate vertical impulse during the long jumper's last steps to the take-off board.

In sum, the data are consistent with a model in which the gait parameter of vertical impulse is directly modulated by the optical variable $\Delta\tau$ in order to bridge the gap between two points of solid support. Irregularity in the spacing of points is, of course, only one type of variation in the ground surface commonly encountered during locomotion. Others include variation in the height of obstacles that must be leaped in the flight phase, and variation in surface slant, friction, and compliance. Whether these properties can also be apprehended visually and negotiated by modulation of vertical or horizontal impulse remains to be determined in further research.

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[1] The results of the long-jump study reported in Lee et al. (1982) showed a high correlation between step length and flight time for the steps the athletes visually regulated when zeroing in on the take-off board. Correlation of step length with flight time was examined because, in the article, it was reasoned that flight time was proportional to vertical impulse. As a general statement, this is inaccurate: The correct relation is as in Equation 3 of the present article—that is, vertical impulse is linearly related to step time. The inaccuracy does not, however, affect the conclusions drawn in the article (namely, that the athletes regulated their strides to the board by changing vertical impulse). The reason is that the long jumpers kept support time about constant, and so variance in step time was due primarily to variance in flight time. Thus we found, on reanalyzing the data for the five adjustment strides given in Table 1 of Lee et al. (1982), that the correlations of step length with step time were in general just as high as the correlations of step length with flight time: .98 versus .70, .99 versus .99, .89 versus .97, .92 versus .96, .84 versus .78.

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(*Appendix follows on next page*)

Appendix

Apportioning the Contributions of Two Variables to the Control of Their Sum

Suppose a variable A can be divided into two additive components X and Y. Thus A can be controlled by adjusting X and/or Y. Only the variable parts of the variables are of interest, so we subtract their means, writing, for example, $a = A - \langle A \rangle$. (Angle brackets denote a mean over measurements.) Then $\langle a \rangle = \langle x \rangle = \langle y \rangle = 0$ and $a = x + y$. Now if x and y are perfectly correlated, x will always be a constant fraction of a, and this fraction is the natural measure of X's contribution to the variable part of A. On the other hand, if x and y are completely uncorrelated, this no longer applies, but the variances of x and y add up to the variance of A; that is, $\langle x^2 \rangle + \langle y^2 \rangle = \langle a^2 \rangle$, so the contribution of X could naturally be measured by $\langle x^2 \rangle / \langle a^2 \rangle$. The problem is to find a measure that corresponds to these results when x and y are either perfectly correlated or perfectly uncorrelated and that also applies in the general case of partial correlation between the two components.

The solution is to split x into two components, one perfectly correlated with a and the other perfectly uncorrelated. This may be written $x = x_c + x_u$, where x_c/a is a constant and $\langle x_u a \rangle = 0$. It may be shown that such a division is always possible and unique. Now it is assumed that if two variables are completely uncorrelated, one cannot be said to control the other. The control of A through X, therefore, resides entirely in x_c, and the measure of the extent of this control is given by x_c/a, which will be denoted by m_x. The same analysis may be applied to y. It may be noted that $m_x + m_y = 1$ and that in the extreme cases of perfect correlation or zero correlation between x and y, these measures reduce to the simple ones given in the last paragraph.

This measure of the contribution of X may be determined from a set of observations using $m_x = \langle xa \rangle / \langle a^2 \rangle$ or, in more familiar terms, $m_x = r(X, A)\, s(X)/s(A)$, where $r(X, A)$ means the correlation of X with A, and $s(X)$ means the standard deviation of X. To show this, we note that $x_c = m_x a$ and so $m_x = \langle a x_c \rangle / \langle a^2 \rangle$. Also, $x = x_c + x_u$ implies $\langle ax \rangle = \langle a x_c \rangle + \langle a x_u \rangle$. Therefore, $\langle ax \rangle = \langle a x_c \rangle$ since $\langle a x_u \rangle$ is zero by definition. Putting these together gives $m_x = \langle ax \rangle / \langle a^2 \rangle$, and this can be rewritten in terms of the correlation and standard deviations simply by using the definitions of correlation and standard deviation. That $m_x + m_y = 1$ may be shown from $x + y = a$, which implies $\langle ax \rangle + \langle ay \rangle = \langle a^2 \rangle$, so $m_x + m_y = (\langle ax \rangle + \langle ay \rangle)/\langle a^2 \rangle = 1$.

The measure m_x is also the slope of the regression line of X on A. Thus the measure can be regarded as the result of fitting the model

$$x = m_x a + e \tag{A1}$$

to the data, where e is an error which is uncorrelated with a. If a control system were to attempt, on each stride, to make x a fixed fraction of the required adjustment to a, but the result was subject to some random error, then m_x would be an estimate of that fraction.

The final property of m_x which is important in the analysis is that it is not biased by errors in determining the point at which A divides into X and Y. Suppose that the point of division between the two is influenced by noise, so that instead of giving x, the measurement yields $x' = x + n$, where n is a random effect in the sense that it is not correlated with a. Then $\langle x'a \rangle = \langle xa \rangle + \langle na \rangle$, and the expectation value of $\langle na \rangle$ is zero. Thus the expectation of $\langle x'a \rangle$ over a set of experiments is $\langle xa \rangle$, and so the expectation of $m_{x'}$ is m_x.

It should be noted that the correlation of X with A does not have the appropriate properties for the measure we require. For instance if X and Y are perfectly correlated, then $r(X, A) = r(Y, A) = 1$, even if the variance in X is a tiny fraction of that in Y. In such a case the measure should assign a much larger number to Y than to X, because Y is clearly producing most of the change in A, and this is indeed what the measures m_x and m_y do. Furthermore, the correlation is biased by noise: Adding random noise to X will make the correlation lower. The meaning of the correlation may be seen in terms of the division of x into x_c and x_u. Then $r(X, A)^2 = \langle x_c^2 \rangle / \langle x^2 \rangle$: The square of the correlation gives the fraction of the observed variance of X that is used in controlling A. The remaining part of x, x_u, is wasted because as far as A is concerned, it cancels out with y_u.

Finally, this analysis is readily extended to multiplicative instead of additive relations, for example, $B = UV$. This may be done simply by writing $A = \log B$, $X = \log U$, $Y = \log V$, $\mathrm{A} = \mathrm{X} + \mathrm{Y}$, and working with A, X, and Y as before. The relation $A = a + \langle A \rangle$ corresponds now to $B = b\{B\}$, where curly brackets designate a geometrical mean over observations. Thus the variable parts of B, U, and V are the adjustment factors, with the properties $\{b\} = \{u\} = \{v\} = 1$, which multiply the geometrical means. The equivalent equation to A1 is

$$u = e b^{m_x}. \tag{A2}$$

As before, $m_x + m_y = 1$, and the error e becomes a multiplier of geometrical mean unity.

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