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Regulation of Gait in Long Jumping

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The way in which gait is regulated to meet the demands of the terrain was investigated by analyzing the movements of skilled long jumpers during their run-up to the takeoff board. The analysis revealed that the run-up consists of two phases: (a) an initial accelerative phase, ending about 6 m from the board, during which athletes attempt to produce a stereotyped stride pattern; and (b) a *zeroing-in* phase, during which they adjust their stride pattern to eliminate error that has accrued. Further analysis revealed that the athletes were regulating a single gait parameter—the vertical impulse, or lift, of their steps. During the stereotyped approach phase they tried to maintain a constant impulse, thereby keeping flight and swing-through time constant. During the zeroing-in phase, they adjusted their flight times (and hence their stride lengths) by regulating the impulse of their steps. The essence of their skill thus appears to lie in the precise adjustment of the impulse toward the end of the run-up. The nature of the visual information that might be used to make the adjustments is discussed.

Although research has increased our understanding of the biomechanics of locomotion and of some of the underlying neurophysiological mechanisms (Alexander & Jayes, 1978; Bernstein, 1967; Cavagna, Thys, & Zamboni, 1976; Grillner, 1975; Grillner, Halbertsma, Nilsson, & Thorstensson, 1979; Herman, Wirta, Bampton, & Finley, 1976; Miller & Scott, 1977; Shapiro, Zernicke, Gregor, & Diestel, 1981; Shik & Orlovskii, 1976), it has been mainly confined to the analysis of uniform gait, as when walking or running straight at a constant speed on a firm, level surface. The normal, cluttered environment rarely allows such straightforward locomotion, however. In general, gait cannot be uniform but has to be constantly regulated on the basis of perceptual information in order to secure adequate footing, negotiate obstacles, and so on. Running down a rough hillside illustrates the point in a dramatic way.

This article is concerned with how gait is regulated to meet the demands of the terrain. The question has been neglected, probably because of the emphasis on the development of theories of prewired gait generators that appear to reveal themselves in uniform gait (see Grillner, 1975, and Shik & Orlovskii, 1976, for reviews). We turned to sports skills that require precise regulation of gait. There are several such skills—high jumping, pole vaulting, hurdling, the steeplechase, for example. We chose long jumping.

In the long jump, the athlete sprints 30 to 40 m and then has to leap off a narrow (.2-m wide) takeoff board. Accuracy of foot placement is at a premium: The athlete's toe needs to be as close as possible to the front edge of the board, since it is from this point that the length of the jump is measured. The foot must not overlap the edge, however; this would invalidate the jump. Speed is also at a premium: The purpose of the run-up to the board is to gain as high a horizontal velocity

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as possible to carry the athlete forward in the jump. A good long jumper, therefore, must be a powerful sprinter. Finally, there is the important factor of the vertical thrust achieved at takeoff, since this determines how long the athlete will remain airborne and hence the length of the jump for a given run-up speed. Over the last few strides—the so-called "gather" phase—the athlete has to get into the right posture for exerting that powerful vertical thrust on the board.

These requirements of speed, accuracy of foot placement on the board, and correct posture at takeoff make the run-up a most demanding task. It is therefore quite surprising how accurately skilled long jumpers can strike the takeoff board; in the present study, their standard error was about 8 cm when traveling at around 9 m/sec (20 mph). How is such accuracy achieved? To be sure, long jumpers try to develop a stereotyped run-up and carefully measure out their starting distance from the board. This can be only part of the story, however: In striking the board with such accuracy, they must, from some point in their run-up, be adjusting their strides in terms of their visually perceived relationship to the board.

By analyzing the movements of skilled long jumpers, we sought first to find out to what extent the run-up is stereotyped and where (if at all) in the run the athletes used vision to regulate their gait to zero in on the takeoff board. We then examined the more detailed question of *how* they were regulating their gait during the run-up. This will require us to briefly examine the mechanical principles of running.

Running is essentially progression by a series of leaps. Thus, two basic actions to be controlled are the thrust exerted against the ground at landing/takeoff and the swinging through of the leg in preparation for the thrust. For running to be smooth and efficient, the power of the thrust—in particular the vertical component—and the speed of the swing-through have to be finely coordinated. This can readily be seen by considering what happens during a gait cycle (see Figure 1). As the left foot leaves the ground and starts its swing-through (having launched the body on a parabolic flight path), the right leg is being swung forward preparatory to driving

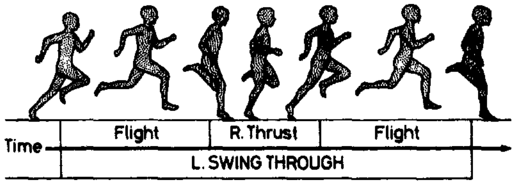

Figure 1. The running cycle. (R. = right; L. = left.)

it backward and downward to strike the ground as the body drops. How the runner strikes and thrusts against the ground is important. First, if the foot is moving forward relative to the ground at strike, either because it is still being swung forward or because it is not being driven back fast enough, then the ground will exert a backward reactive force on the foot that will slow the runner down. Thus, skilled runners take care to get a sufficiently high knee lift so that they can drive the leg down and backward fast enough, striking the ground just forward of the hips (Dyson, 1978). Second, and more critical, if the thrust does not give the body sufficient lift (i.e., if the vertical component of the launch velocity is not high enough), then the succeeding flight phase will be too short; there may then not be enough time for the other leg to be swung through and driven down properly. This could lead to the next thrust-off being inadequate and, unless corrective action were quickly taken, the situation could escalate until the runner stumbled and fell.

Sprinting (as in the long jump) poses a more difficult problem in controlling thrust and swing-through than does steady-speed running. Indeed, it is not too unusual to see control break down and a sprinter fall in midrace. For, whereas the long-distance track runner can keep thrust and swing-through practically constant, thereby maintaining a steady rhythm, this is not physically possible for the sprinter: Thrust and/or swing-through have to be mutually adjusted as the runner gathers speed. The reason is that the length of time the foot is on the ground (the thrust time) gets shorter as speed increases. Thus, the impulse (Thrust Force × Time) that the runner obtains by thrusting with a certain force decreases. For instance, if the thrust force was kept constant in both magnitude and direction, then the vertical impulse would decrease as speed increased, with the result that flight time would also decrease (since it is proportional to the vertical impulse) and so the swing-through would need to be speeded up. Our analysis will examine how the long jumpers co-regulated thrust and swing-through in attempting to strike the takeoff board accurately.

Method

Subjects

Three female athletes took part in the study: MN, a 22-year-old British International long jumper of Olympic standard, whose best jump was 6.54 m; VW, a 19-year-old Scottish International long jumper, whose best jump was 6.03 m; and FM, an 18-year-old Scottish International 100 m hurdler and good club long jumper, whose best jump was 5.78 m. Each athlete had trained to develop a consistent run-up, used a standing start from a measured mark, and jumped from her right foot. None used check marks down the track. MN used a 21-stride run starting about 40 m from the board, VW an 18-stride run starting at about 32.10 m, and FM a 19-stride run starting at about 34.40 m.

Procedure

Each athlete was filmed during two normal training sessions about 1 week apart. A session comprised either six jumps or six "run-throughs" (i.e., practice run-ups where the athlete did not actually jump). Filming was done at Meadowbank Stadium, Edinburgh, where the Tartan long-jump track runs along the foot of a spectators' stand. A 16-mm Bolex movie camera was mounted at the back of the stand, about 30 m from the track, and was panned to follow the athlete down the track. The films were shot through a telephoto lens of 50-mm focal length at 48 frames/sec, with a 1/300 sec shutter speed. To record the positions on the track of the athlete's footfalls (and hence the stride lengths), a black marker strip with white stripes at 10-cm intervals and longer stripes at 1-m intervals was laid down each side of the track. The positions of the athlete's footfalls could then be measured from single frames of the film by lining up the athlete's toe with corresponding points on the two marker strips, as illustrated in Figure 2. A test showed that the method of measurement was ac-

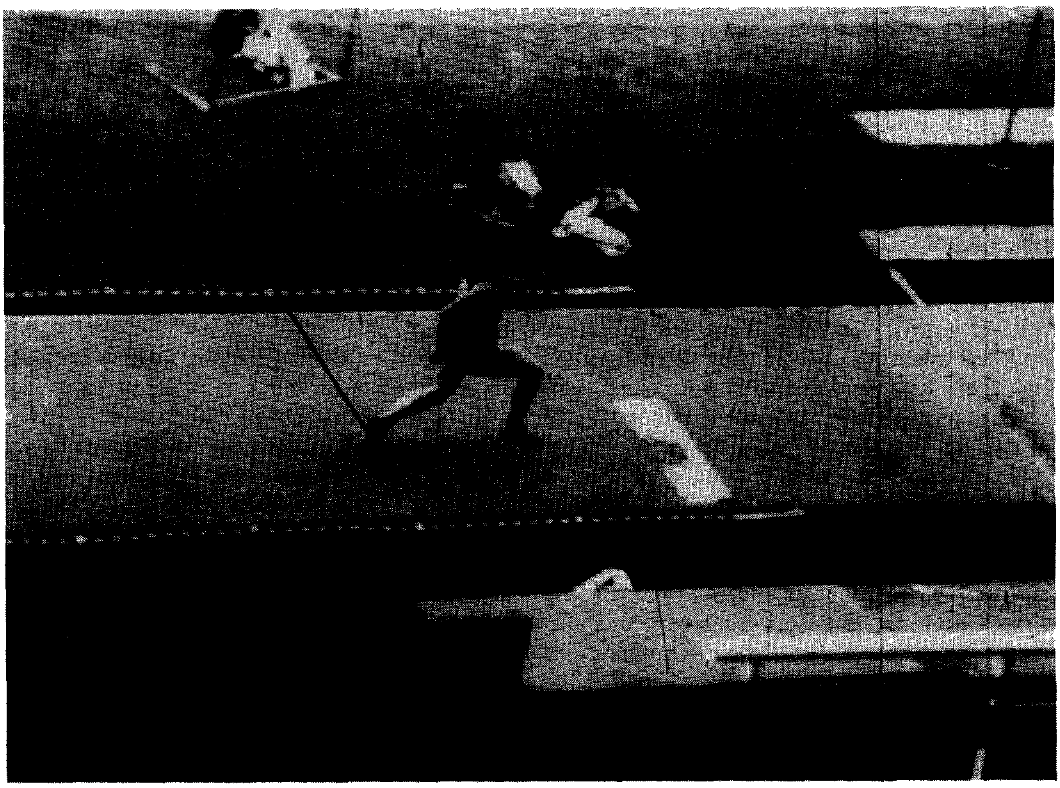

Figure 2. How the distances from the takeoff board of the long jumpers' footfalls were measured from the film frames. (A straight edge, illustrated by the black line, was laid across the projected picture to line up the athlete's toe with corresponding points on the marker strips, which had been placed down the sides of the track. Measurements were accurate to about 1 cm.)

curate to about 1 cm. The duration of the athletes' strides was estimated by counting film frames; the standard error of estimate was about 10 msec.

Results and Discussion

The Two Phases of the Run-Up

The top six graphs in Figure 3 show the mean stride patterns for the six training sessions (three athletes, two sessions each). During the approach phase of their run-ups, until they were a few strides from the board, the athletes maintained consistent stride patterns, as is evidenced by the small standard errors of their stride lengths (about 3 cm on average). This consistency, which presumably reflects the athletes' training, is remarkable in that, as Figure 3 shows, the athletes were not merely keeping stride

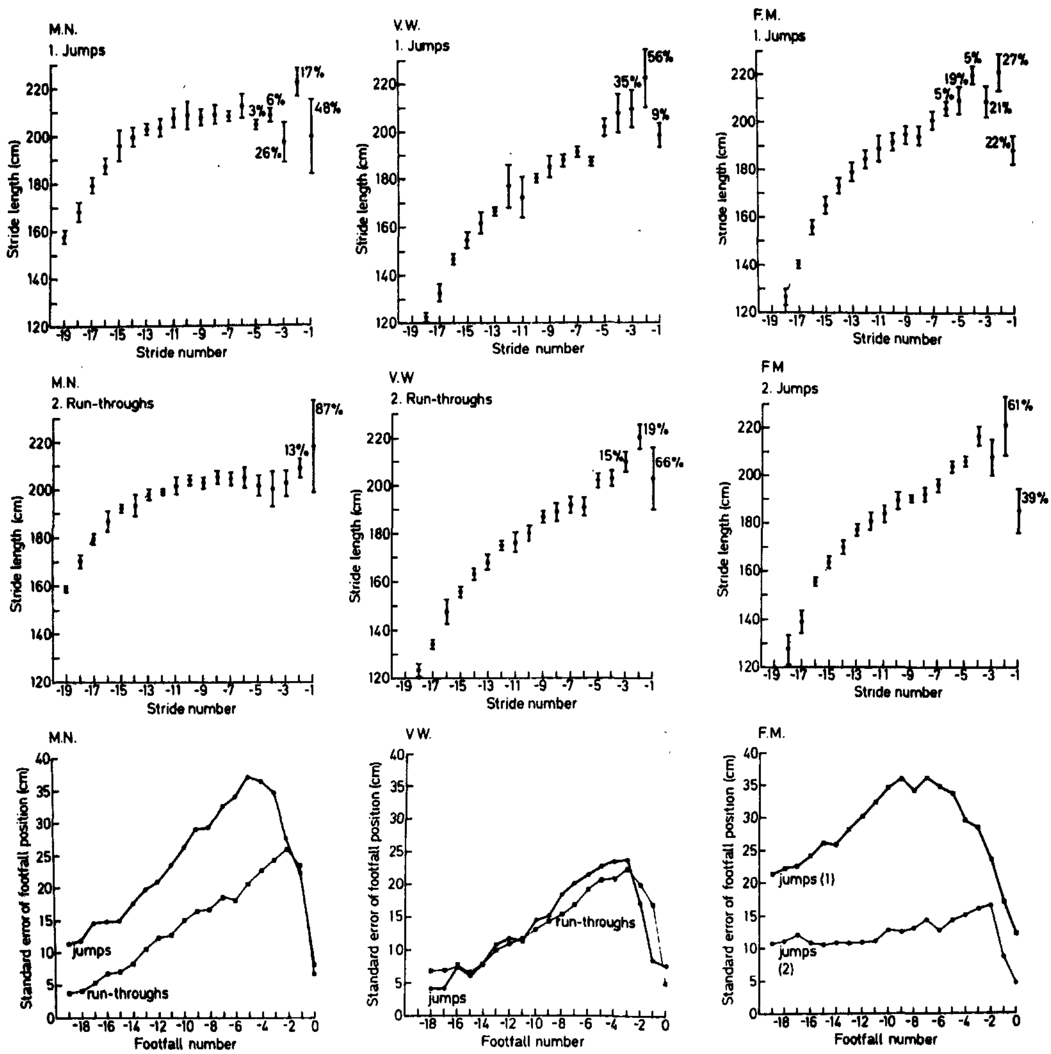

Figure 3. Each of the top six graphs shows the means and standard errors of stride lengths over a training session of either six jumps or six run-throughs for the three athletes, MN, VW, and FM. (MN's first two strides and FM's first stride are not shown. Stride −1 is the stride onto the takeoff board, Stride −2 is the preceding one, etc. The numbers printed over the strides are statistical estimates of the percentage adjustment that was made on that stride; see text for details. The bottom three graphs show the standard errors of the distances of the athletes' footfalls from the takeoff board. Footfall 0 is the one aimed at the board, footfall −1 is the penultimate one, etc.)

length constant but were progressively increasing their stride lengths in a systematic manner as they accelerated down the track. In the next section we tackle the question as to how they did this.

A second point to note in the top six graphs of Figure 3 is that the consistency of the athletes' stride patterns broke down over their last few strides to the board. The reason for this is clear from the bottom row of graphs in Figure 3. As the athletes ran down the track, the small inconsistencies in their stride lengths had a cumulative effect, so that, for instance, by the time the Olympic athlete (MN) was five strides from the board, the standard error of her footfall position had risen to 37 cm. Had she continued blindly on, her standard error at the board would have been even larger. That is not what happened, however. As with the other athletes, the standard error of her footfall positions decreased rapidly (to 8 cm) over her last few strides to the board.

There seems to be only one explanation for this rapid decrease: The athletes were visually adjusting their final strides to zero-in on the board. In other words, as they neared the end of their run they switched from trying to produce a stereotyped stride pattern to regulating their strides in terms of their visually perceived relationship to the board, in order to hit it.

The bottom graphs of Figure 3 show that the athletes did not apportion the adjustment required to hit the board equally among their final strides; some strides produced a greater reduction in the standard error of footfall position than did others. Estimates of the percentage of the total adjustment made on individual strides are presented in the top six graphs of Figure 3. The percentages are the coefficients, m, in computed linear regression equations of the form $l = m \times d$, where l represents the amount by which a particular adjustment stride was lengthened or shortened in relation to its mean length over the six runs, and d represents the amount by which the total distance covered by the adjustment strides was increased or decreased in relation to its mean.

Note that the athletes varied between sessions in the number of strides they adjusted and in how they apportioned their total adjustment across the strides. Two points seem to emerge. First, the less consistent the approach run (i.e., the greater the buildup of the standard error of footfall position down the track), the more strides were visually adjusted at the end (compare, e.g., FM [1] with FM [2]). This makes sense in that the greater the error that is accruing, the sooner will the error become detectable, and so the sooner before reaching the board can action be taken. Second, to avoid disrupting the gather for the jump, it would be advantageous to spread out the required adjustments over as many strides as possible. This relates to the other point that emerges from the data: In their run-throughs, the athletes (MN and VW) did *not* spread out their adjustment but left most of it to the last stride. This is understandable in that they did not *have* to strike the board in a particular posture as they would have to do when jumping. It does call into question, however, the value of run-throughs as simulations of run-ups for a jump.

Control of Gait During the Approach Phase

In attempting to determine which parameter(s) of gait the athletes were regulating, we first examined in more detail the approach phase of their run-ups (i.e., up to the point where they started to guide themselves onto the board). As we have pointed out, the athletes made no attempt to maintain a constant stride length but progressively lengthened their strides in a consistent way as they accelerated down the track (see Figure 3). Given that they were trying to span the distance between their start mark and the board with a fixed number of strides, this would appear to be a rather complex way of going about the task. It might be argued that it would have been simpler just to keep stride length constant rather than having to "remember" and reproduce a whole sequence of differing stride lengths. However, this is to ignore the mechanics of running. We have pointed out that a basic problem any sprinter confronts is coordinating thrust and swing-through during acceleration. Let us examine how the long jumpers dealt with the problem.

Figure 4 shows the basic data. The first point to note is that the flight time did *not* decrease as speed increased. (Shapiro et al., 1981, found the same in treadmill running at different constant speeds.) From this we can infer that the vertical impulse (Vertical Component of Thrust × Thrust Time) was nondecreasing. Since thrust time was getting

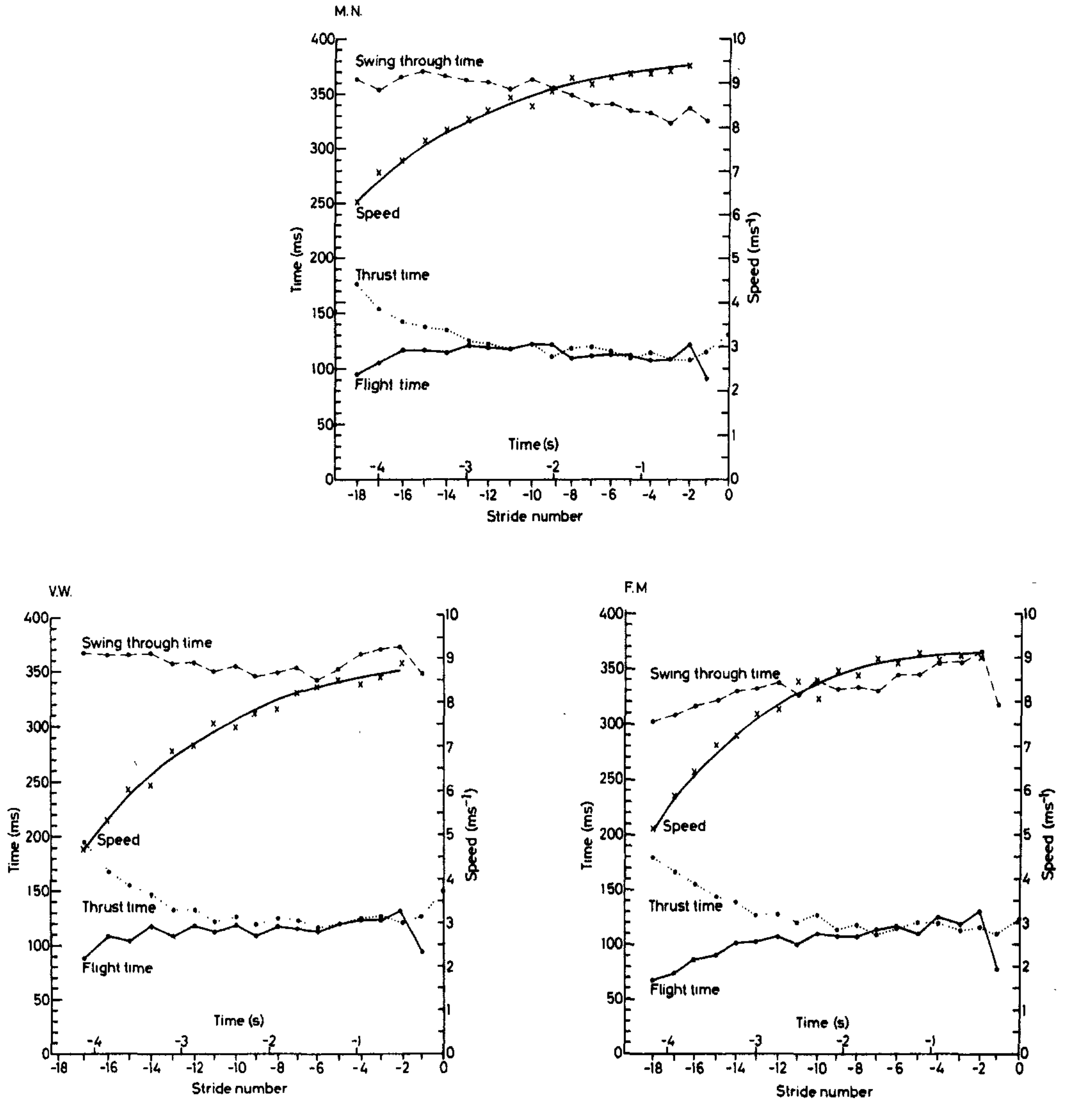

Figure 4. Showing how flight time, thrust time, swing-through time and speed changed as the long jumpers sprinted down the track. (The smooth curves through the speed points are predictions from the theory given in the text. Mean data over two training sessions for each athlete are given. MN's first three strides and VW's and FM's first strides are not shown. On the abscissae: Stride −1 is the stride onto the takeoff board, Stride −2 is the preceding one, etc. "Time" refers to the interval between the footstrike immediately prior to launching the stride and the footstrike on the board. "Thrust time" is the foot-ground contact time at the start of the stride. "Flight time" is the airborne period of the stride. Standard error of measurement was about 10 msec. Standard deviations of the measured times across runs were on average about 9 msec for the thrust and flight times and about 13 msec for the swing-through times. "Speed" is the ratio of stride length to the sum of the thrust and flight times. Standard deviations of the computed speeds across runs were on the average about .31 m/sec.)

shorter with increasing speed, it follows that the athletes were compensating by progressively increasing the vertical component of their thrust as they accelerated.

In what way were they doing this? They could not have simply been thrusting harder the faster they ran, keeping the direction of the thrust constant; their horizontal impulse would then have been nondecreasing; thus, their acceleration would not have fallen off as it did (see Figure 4). Given that speed was at a premium, it seemed to us that the most likely hypothesis was that they were thrusting with a *constant* force (about as hard as they could) and by progressively steepening the angle of the thrust were increasing the vertical component in such a way as to keep the vertical impulse constant. This pattern of action would result in the horizontal impulse (and hence, the athletes' acceleration) decreasing in a specific way. The theory can therefore be tested against the athletes' speed data. The smooth curves through the speed points in Figure 4 are predictions from the theory, which is spelled out in Appendix A. It will be seen that the curves closely fit the data.

It might appear that a further test of the theory could be made in terms of the athletes' flight times. In particular, it might be argued that if the athletes were keeping their vertical impulses constant, then their flight time should be constant too. However, although this argument is valid for long-distance track running, it is not valid for sprinting. The difference is that long-distance runners strike the ground in a cyclically regular way (or at least aim to), with knee and hip flexed a certain amount and the center of gravity at the same height at each footstrike. Sprinters, on the other hand, in order to generate a powerful horizontal thrust, start with the body leaning forward, greater flexion at knee and hip, and a low center of gravity. Then, as they gather speed and have to direct their thrust more vertically in order to maintain adequate lift, they gradually straighten up, raising the center of gravity. By striking the ground when the center of gravity is at successively higher points, they are cutting short their flight times—the more so the greater the rise in height between footstrikes. A constant vertical impulse theory would predict that the long jumpers' flight times should be shorter during the first part of their run-up when they were progressively straightening up. The flight time data (see Figure 4) do, in fact, follow this pattern and therefore add some further support to the theory (for details, see Appendix B).

Control of Gait During the Final Phase

We have explained how the complex stride patterns produced by the long jumpers during the approach phase could have simply been the result of keeping constant the vertical impulse of their steps (while thrusting about as hard as they could to optimize speed). Consider now the state of affairs when the athletes were a few strides from the board. They had reached a more or less steady state: Speed, thrust time, flight time, and swing-through time were all about constant (see Figure 4). However, if they had continued in that steady state they would in general have missed the board. They therefore had to visually regulate their remaining strides. Could it be that here, as in the approach phase, the kinetic parameter they regulated was the vertical impulse of their steps?

The length of a stride is the horizontal distance traveled by the hips from the point where they are vertically above one support foot to the point where they are vertically above the next (i.e., from the position of the third figure to the position of the seventh figure in Figure 1). Stride length comprises three segments, the lengths of which are independently controllable. First, there is *thrust length*, the horizontal distance moved by the hips from the start of the stride to the point when the foot leaves the ground. Thrust length depends basically on the height of the hips at takeoff (see Figure 1). Second, there is *flight length*, the distance travelled by the hips when the body is airborne. Since flight length is the product of horizontal speed and flight time, it can be modulated by adjusting either the horizontal impulse, the "drive" of the thrust, or the vertical impulse, the "lift" of the thrust, or both. The final segment of the stride is *landing length*, the distance moved by the hips from the point when the foot strikes the ground to when the hips are over the foot. Landing length can be increased by reaching forward with the foot. However, as we have pointed out, striking the ground with the foot ahead of the hips generally results in a retarding force being applied to the body; efficient running consequently entails keeping landing length short.

In order to determine which parameter(s) of their strides—thrust length, flight speed, flight time, or landing length—the athletes were adjusting to alter their stride lengths, we calculated the correlations between stride length and each parameter (or a correlate of it). A high positive correlation would indicate that a particular parameter was being adjusted. Because of perspective distortions in the film records produced by panning the camera, it was not possible to measure accurately thrust length and landing length as such. We chose as reasonable correlates of these parameters *thrust time* and *landing time* (i.e., the foot–ground contact times at the start and end of the stride). Flight speed was calculated by dividing stride length by stride time, the latter being taken as the flight time plus the average of the thrust time and landing time. Finally, in order that the correlations should be meaningful and not too distorted by measurement error, we selected for analysis those strides that showed a standard deviation in length that was greater than the error of estimate of the stride parameters. Since the standard error of measurement of the temporal parameters was about 10 msec and the athletes' speed was around 10 m/sec this corresponded to a distance measurement error of about 10 cm. Accordingly, we only analyzed those strides with a standard deviation of length greater than 10 cm.

The results (see Table 1) indicate that flight time was the principal stride parameter being adjusted. The correlation with stride length was consistently high, which was not so for any of the other stride parameters. This makes sense in that, for instance, increasing flight time would disrupt gait less than increasing thrust length, which would entail lowering the hips, or increasing landing length, which would retard the body.

Thus, control throughout the run-up appears to consist in regulating just one kinetic parameter, the vertical impulse of the step—keeping it constant during the approach phase and then adjusting it to regulate flight time in order to strike the board.

General Discussion

We started with the question, How is gait regulated to meet the demands of the terrain? By analyzing the movement of skilled long jumpers during their run-ups to the takeoff board, we attempted to gain some insight into the control system.

Our initial analysis revealed that during the accelerative approach phase of the run-up, the long jumpers produced fairly stereotyped stride patterns. However, positional errors accrued as they moved down the track; they had to regulate their last few strides in order to zero in on the takeoff board.

Our second, more detailed analysis, sought to answer two questions: (a) How were the athletes controlling their gaits while accelerating so as to generate consistent, though nonuniform, stride patterns? (b) What adjustments were they making to their gait when zeroing in on the board? The results indicated that both in the approach phase and in the zeroing-in phase of the run-up the athletes were essentially regulating one kinetic parameter of their gaits, namely the vertical impulse, or lift, of their steps. During the accelerative approach phase, they aimed to keep the vertical impulse constant while keeping the magnitude of the thrust constant; this entailed progressively steepening the direction of the thrust to compensate for the progressive shortening of thrust time as speed built up. The strategy had the advantage that flight time and swing-through time were kept about constant. Finally, during the zeroing-in phase the athletes regulated the vertical impulse of their steps to adjust their flight times in order to strike the board.

There is little doubt that the final phase was visually guided. But what type of visual information might the athletes have been using? The finding that they were adjusting their flight times rather than the spatial parameters of their gait (thrust length and landing length) suggests that they were using information about how far in time they were from the board.

How could the athletes have detected the time-to-contact with the board? One might suppose that they would have to perceive both their speed and distance from the board and compute time-to-contact. This is not necessarily so, however. In the optic flow field at the athlete's eye, *time-to-contact* is specified directly by a single optical parameter, the inverse of the rate of dilation of the image of the board; this parameter is essentially unperturbed by eye movements or by the up–down and lateral movements of the head when running (Lee, 1976). Schiff and Detwiler (1979) and Todd (1981) have demonstrated experimentally, by manipulating the rate of dilation of images in movie and computer displays, that time-to-contact can in fact be visually perceived in the absence of information about distance and velocity. Thus the time-to-contact optic parameter would certainly seem to be a viable source of information for the long jumper. It is, furthermore, easy to see how the athlete might have used the time-to-contact information to regulate the vertical impulses of her steps to strike the board. With the support periods constant, as our data indicate, the athlete's task becomes regulating the flight times of the remaining strides to just fill the time available for flight (i.e., the time-to-contact minus the support times). But flight time is *proportional to vertical impulse*. Therefore, the mean fractional adjustment the athlete needs to make to the impulses of her remaining strides is simply equal to the ratio t'_f/t_f (where t'_f—which is specified by the time-to-contact—is the required average flight time of the remaining strides, and t_f is the current flight time). Thus, the adjustment during the final phase might have been based on a single visual parameter—just as gait was regulated by a single kinetic parameter, vertical impulse. This interpretation would certainly be consistent with the remarkable fluency of the athletes' movements, a feature that constantly impressed us.

Table 1
Analysis of Adjustment Strides

Athlete (session)	Stride no.	Stride length (cm)	Thrust time (msec)	Flight time (ms)	Flight speed (m/sec)	Landing time (msec)
MN (1)	−1					
M		199	111	73	10.08	135
SD		14	10	10	.26	10
r			.69	.70	.43	.23
MN (2)	−1					
M		218	89	151	8.88	102
SD		18	8	25	.21	4
r			.01	.99	−.73	−.55
VW (1)	−2					
M		222	100	150	8.54	121
SD		11	5	14	.18	5
r			−.20	.97	.21	−.63
VW (2)	−1					
M		203	102	123	8.69	119
SD		12	7	15	.15	8
r			−.58	.96	−.55	.81
FM (2)	−2					
M		222	115	131	9.12	108
SD		11	10	10	.12	3
r			.42	.78	.80	−.07

Note. The correlations (*r*) are between the respective stride parameters and stride length. Notice, in general, the high correlations and standard deviations for flight time, indicating that it was this stride parameter that was primarily being adjusted. MN (2) and VW (2) were "run-through" sessions; the remainder were jump sessions.

It seems possible that the visual information we have outlined is used in other skills requiring precise timing. Take, for instance, the ski jump. Here, jumpers in crouched position accelerate under gravity down the steep in-run, reaching speeds of 25 m/sec (56 mph) or more. Just before reaching the lip of the in-run, they have to rapidly straighten their legs in order to launch themselves. The takeoff has to be timed very accurately. Thus, the ski jumpers and long jumpers are faced with the same problem—that of detecting visually, with adequate accuracy, the time-to-contact with the takeoff point. We have also found that much the same timing accuracy was achieved by Olympic ski jumpers as by the long jumpers.[1] The ski jumpers started straightening their legs on average 194 msec before their feet passed over the lip of the in-run; the standard deviation of this time interval for 14 jumpers was a mere 10 msec. In comparison, the timing accuracy of the long jumpers was about 9 msec (the standard distance error of 8 cm at the board divided by the mean approach speed of 9 m/sec.

There are numerous other skills, from catching or hitting a ball to Grand Prix racing, that similarly require accurate visual detection of time-to-contact. Driving, in fact, would seem to provide a rather subtle example of the use of the optical parameter specifying time-to-contact (under constant velocity). Evidence indicates that in stopping for an obstacle, drivers control their braking in terms of the time derivative of the optical parameter; the value of the time derivative specifies whether or not the current braking force is adequate to stop before the obstacle (Lee, 1976).

Visual information about time-to-contact is not, of course, solely a human prerogative. The information is available to any seeing organism and, indeed, is needed for many activities. Gannets (*Sula bassana*), for example, appear to use the time-to-contact optical parameter in timing their wing closure when plunge-diving at high speed into the sea (Lee & Reddish, 1981).

Finally, let us briefly return to the example we gave at the beginning of the article—running (or skiing) down a rough mountainside. How do the ideas we have put forward apply to these more complex cases? There the ground is littered with possible takeoff points as well as potential hazards and the task, whether running or skiing, is to move smoothly from one takeoff point to the next. Clearly, compared with long jumping, another dimension of control is involved, namely the direction each leap (stride, jump) should take, for in general the route will have to zig-zag. The runner or skier therefore needs visual information about the relative orientations of successive legs of the route ahead to be able to launch off in the right direction; that information, too, is directly available in the optic flow field at the eye (see, e.g., Lee, 1980). The remaining dimension of control, however, is just the same as for the long jumper. The vertical impulse, the lifting drive of each thrust, has to be visually regulated in terms of time-to-contact so that the body is in flight just long enough to land on the next support point.

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[1] Films of 14 ski jumpers on the 70-m jump were analyzed in collaboration with T. K. Pitcairn. The films, kindly loaned by C. Dillman, were shot at 128-frames/sec at the 1979 Winter Pre-Olympic Games, Lake Placid, New York.

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Appendix A

Derivation of Predicted Speed × Time Curves Shown in Figure 3

The theory is that during the approach run, the athletes were thrusting on the ground with a constant impulsive force (F) on each step and were obtaining a constant vertical component of impulse (I_V) by regulating the direction of the thrust. If this were so, then the horizontal component (I_H) of the impulse would be

$$I_H = \sqrt{F^2 t_{th}^2 - I_V^2} \qquad \text{(A1)}$$

for $t_{th} \geqslant I_v/F$, where t_{th} is the duration of the thrust. If the distance travelled by the hips during the thrust is d, and s is the athlete's speed, then

$$t_{th} = d/s. \qquad \text{(A2)}$$

Substituting for t_{th} in equation (A1),

$$I_H = \sqrt{F^2 d^2/s^2 - I_V^2} \qquad \text{(A3)}$$

for $0 < s \leqslant Fd/I_v$. The horizontal impulse (I_H) generated during the thrust phase will increase the athlete's speed by

$$\Delta s = I_H/M, \qquad \text{(A4)}$$

where M is the athlete's mass. Speed will then remain constant during the flight phase (assuming air resistance is negligible). Therefore, from equations (A3) and (A4), the average acceleration during the stride will be

$$\Delta s/t_s = \sqrt{F^2 d^2/s^2 - I_V^2}/Mt_s\,, \qquad \text{(A5)}$$

where t_s is the duration of the stride. Approximating by taking the acceleration to be smooth we have

$$ds/dt = \sqrt{F^2 d^2/s^2 - I_V^2}/Mt_s \qquad \text{(A6)}$$

for $0 < s \leqslant F_d/I_v$.
To a good approximation, t_s and d may be taken to be constants for each athlete (from the film analysis, t_s = 239 ± 8, 247 ± 10, 234 ± 9 msec, and d = 1.01 ± .09, .94 ± .08, .98 ± .09 m for MN, VW, and FM respectively, d being computed using Equation A2. Integrating Equation A6 we obtain the general equation of the theoretical curves in Figure 3,

$$s^2 = A^2 - B^2(t_a - t)^2 \qquad \text{(A7)}$$

for $0 < s \leqslant A$ and $t_a - A/B < t \leqslant t_a$, where $A = Fd/I_V$, $B = I_V/Mt_s$, and t_a is the time at which the speed s reaches its maximum value, A. The equations of the curves of Figure 3 were determined by selecting three points, one at each end and one in the middle of the data range, substituting the coordinates of the points in Equation A7 and solving for the parameters A, B, t_a, which yielded (A, B, t_a) = (9.39, 1.72, .03), (8.75, 1.78, .28), and (9.10, 2.16, .43) for MN, VW, and FM, respectively.

Appendix B

Effect on Flight Time of Straightening Up Over the First Strides

To optimize their acceleration, sprinters start with their center of gravity (CG) low and steadily raise it stride by stride until the body is erect. If the vertical impulse at footstrike is kept constant, then during this progressive raising of the CG, flight time will be curtailed. The relationship between the increase in height of the CG and the reduction in flight time is as follows.

If $\hat{t}_f$ = flight time when body erect, t_f = flight time when CG is being stepped up a height h, H = maximum rise of CG during flight period of a stride, and g = gravitational acceleration, then, for $t_f \geqslant \hat{t}_f/2$,

$$t_f = \hat{t}_f/2 + \sqrt{2(H - h)/g}$$

and

$$H = g\hat{t}_f^2/8.$$

Eliminating H,

$$h = gt_f(\hat{t}_f - t_f)/2. \qquad (A8)$$

The values of h, the rise in the CG with each of the early strides, was calculated from the flight-time data using Equation A8. The height changes could not be directly measured from the films with sufficient accuracy. However, the estimated values seem reasonable. MN was estimated to raise her CG 43 mm, VW 22 mm, and FM 42 mm. Although these values seem low, the athletes used a standing start rather than a crouch start. The main point is that the increase in flight time over the first few strides is entirely consistent with the notion of constant vertical impulse and a rising CG.

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