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Faster top running speeds are achieved with greater ground forces not more rapid leg movements

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Weyand, Peter G., Deborah B. Sternlight, Matthew J. Bellizzi, and Seth Wright. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991–1999, 2000.—We twice tested the hypothesis that top running speeds are determined by the amount of force applied to the ground rather than how rapidly limbs are repositioned in the air. First, we compared the mechanics of 33 subjects of different sprinting abilities running at their top speeds on a level treadmill. Second, we compared the mechanics of declined (-6°) and inclined ($+9^\circ$) top-speed treadmill running in five subjects. For both tests, we used a treadmill-mounted force plate to measure the time between stance periods of the same foot (swing time, t_{sw}) and the force applied to the running surface at top speed. To obtain the force relevant for speed, the force applied normal to the ground was divided by the weight of the body (W_b) and averaged over the period of foot-ground contact (F_{ave}/W_b). The top speeds of the 33 subjects who completed the level treadmill protocol spanned a 1.8-fold range from 6.2 to 11.1 m/s. Among these subjects, the regression of F_{ave}/W_b on top speed indicated that this force was 1.26 times greater for a runner with a top speed of 11.1 vs. 6.2 m/s. In contrast, the time taken to swing the limb into position for the next step (t_{sw}) did not vary ($P = 0.18$). Declined and inclined top speeds differed by 1.4-fold (9.96 ± 0.3 vs. 7.10 ± 0.3 m/s, respectively), with the faster declined top speeds being achieved with mass-specific support forces that were 1.3 times greater (2.30 ± 0.06 vs. $1.76 \pm 0.04 F_{ave}/W_b$) and minimum t_{sw} that were similar ($+8\%$). We conclude that human runners reach faster top speeds not by repositioning their limbs more rapidly in the air, but by applying greater support forces to the ground.

locomotion; running performance; running mechanics

THE IMPRESSIVE SPEEDS OF THE swiftest human and animal runners are believed to be promoted by anatomic and physiological features that increase both the frequency and length of their strides. Slender legs with relatively fast muscle fibers presumably increase stride frequencies by allowing limbs to be repositioned more rapidly (11, 14, 15, 17, 30) and long limbs are

believed to extend stride lengths by providing greater forward propulsion (11, 14, 15, 17, 30). Although these mechanisms are widely accepted, their actual contributions to the faster top speeds of swifter runners are not known. The greater maximal frequencies of runners with faster muscle fibers (2, 7, 13) could be achieved by reducing the portion of the stride the foot is in contact with the ground rather than the portion taken to swing the limb into position for the next step. If the mechanical energy to reposition limbs is provided largely passively through elastic recoil and energy transfers between body segments (12, 19, 29), rather than actively by power generated within muscles (11, 15, 30), minimum swing time would be affected minimally by muscle fiber speeds. Similarly, longer strides do not necessarily require longer legs. At top speed, human sprinters take strides considerably longer than those of non-sprinters, although their legs are of similar length (2). One means of achieving longer strides would be to apply greater support forces to the ground. At any speed, applying greater forces in opposition to gravity would increase a runner's vertical velocity on takeoff, thereby increasing both the aerial time and forward distance traveled between steps.

Here, we hypothesized that greater ground forces, rather than shorter minimum swing times enable human runners to reach faster top speeds.

METHODS

Experimental Design

Our two experimental tests of the hypothesis that top speeds are determined by the amount of force applied to the ground rather than how rapidly the limbs are repositioned in the air began with the elementary mechanics of running speed. Speed is simply the product of the frequency (Freq) and length (L) of a runner's steps

$$\text{Speed} = L_{\text{step}} \cdot \text{Freq}_{\text{step}} \quad (1)$$

where L_{step} and $\text{Freq}_{\text{step}}$ are defined as the distance and time, respectively, between consecutive footfalls. Thus a first possibility is that runners might attain faster top speeds simply by taking more frequent steps. Alternatively, faster top

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speeds might be achieved by traveling farther between steps, a feat mechanically possible in either of two ways. During constant-speed running, the distance traveled between steps is determined by the product of the average mass-specific force applied to oppose gravity during foot-ground contact ($F_{\text{avge}}/W_b = F/F_{W_b}$, where W_b is the weight of the body) and the forward distance the body moves during this contact period (contact length, L_c). The average mass-specific force that a runner applies to the ground to oppose gravity during the contact period equals the ratio of the total step time (t_{step}) to the foot-ground contact time (t_c)

$$F_{\text{avge}}/W_b = t_{\text{step}}/t_c \quad (2)$$

The fraction of the total step time the foot is in contact with the ground equals the fraction of the total L_{step} traveled during the foot-ground contact period

$$t_{\text{step}}/t_c = L_{\text{step}}/L_c \quad (3)$$

Rearranging Eq. 3 ($L_{\text{step}} = L_c \cdot t_{\text{step}}/t_c$) and substituting F_{avge}/W_b for t_{step}/t_c allows step lengths to be expressed as the product of contact length and the average vertical force applied during the period of foot-ground contact

$$L_{\text{step}} = L_c \cdot F_{\text{avge}}/W_b \quad (4)$$

Thus the three mechanical means by which runners might achieve faster top speeds can be expressed in a single equation as

$$\text{Speed} = \text{Freq}_{\text{step}} \cdot F_{\text{avge}}/W_b \cdot L_c \quad (5)$$

We anticipated that differences in the top speeds of human runners would be determined not by step frequencies and contact lengths but by the amount of force applied to the running surface for several reasons. First, swing time comprises the majority of the total stride time and therefore is the primary determinant of the frequency of a runner's steps, and the range of stride frequencies used by terrestrial runners at different speeds tends to be narrow (13). Thus we expected little variation in step frequencies at top speed. Second, available evidence suggests that the human contact lengths at intermediate and high speeds do not vary appreciably (16, 20, 21) and that faster human runners take considerably longer strides (2, 5). These results imply that faster runners apply greater support forces to the ground.

The first test of our hypothesis was to have 33 subjects of different sprinting abilities run to top speed on a level treadmill. We predicted the contact lengths, stride frequencies, and swing times of fast and slow runners would not differ but that the support force applied to the ground would be greater for faster vs. slower runners.

To maximize the range of top running speeds attained by our subjects, we included both male and female subjects. Although small differences in running mechanics might be present between male and female runners, several considerations suggested that such differences, if present, would not confound this experimental test. First, the quantitative test of our hypothesis expressed in Eq. 5 applies equally to male and female runners. Second, the functional properties of the skeletal muscles that apply ground force and swing limbs (6) do not differ between men and women. Third, the difference in performance between equally trained male and female runners results from the greater proportion of the body's weight made up of fat in females (28). Fourth, the gender difference in world record running performances for three Olympic sprint events ($9.3 \pm 1.8\%$) closely matches the gender difference in percent body fat (i.e., 10%).

We recognized that individual variation in step frequencies and contact lengths not directly related to top speed might exist among the 33 subjects participating in our first test; therefore, we undertook a second test designed to alter F_{avge}/W_b while holding step frequency and contact length constant. We had the same runners run to top speed on -6° and $+9^\circ$ treadmill inclinations. Comparing subjects to themselves across these conditions provided a statistically and biologically more robust test with respect to individual variability. The mechanical determinants of speed described by Eq. 5 apply equally to declined, inclined, and level treadmill running. In each case, the height of the center of mass does not change over time, and F_{avge}/W_b represents the average force applied normal to the earth (i.e., support force) during the period of foot-ground contact.

Our hypothesis for the second test was virtually identical to that of the first test: we predicted runners would reach higher declined than inclined top speeds by applying greater vertical forces to the running surface while repositioning their legs in the same minimum time.

Meeting our experimental objective required measurements of the vertical but not the horizontal component of the ground reaction force. During constant-speed running, the peak vertical ground-reaction forces are typically 5–10 times greater than the peak horizontal forces (24). When one runs at a constant speed against no air resistance, the propulsive forces that increase the body's forward velocity before takeoff simply offset the braking forces that decrease the body's velocity on landing. In the present experiment, both the net horizontal forces exerted to propel the body forward and the effect of these forces on forward speed must be zero regardless of the top speed attained by the runner or the inclination of the treadmill. Because the net horizontal forces our subjects exerted during each stride could not explain differences in the top speeds attained, they were not included in our analysis.

We conducted our experiments on a treadmill rather than a track or level terrain to facilitate direct measurements of surface reaction forces and running mechanics. This enabled us to eliminate the different resistances that our fast and slow subjects would encounter from air at their different top speeds (25), as well as the mechanical variability that occurs when subjects run at volitional rather than controlled speeds. However, we believe our results will generalize to over-ground running for two reasons. First, the mechanical variables included in our analysis are affected little by the characteristics of the running surface (9) or surface inclination (16). Second, the mechanical requirements to apply sufficient force normal to the earth to support the body's weight against gravity and for some minimum time to be taken to reposition the limb for the next step are similar under all of these conditions.

Subjects

Twenty-four men [74.4 ± 8.0 kg (SD)] and nine women (60.8 ± 5.8 kg) who were physically active and between 18 and 36 years of age participated in the study. All subjects provided written, informed consent after the benefits and risks of the experimental procedures were explained to them, in accordance with the guidelines of Harvard University.

Measurements

Top speed. Subjects performed a 10-min warmup at a comfortable jogging speed, typically 2.5 m/s. They were then strapped into an upper-body harness suspended from the ceiling to prevent them from falling and being propelled

behind the treadmill during the test. The chest harness and slackened ceiling suspension did not impede or assist the subjects' running mechanics in any way. The test was initiated at 3.0 m/s with subsequent speed increments of 1.0 m/s through intermediate speeds, and 0.1–0.5 m/s thereafter, in accordance with subject feedback regarding difficulty. Subjects were instructed to recover fully between speeds, which typically took 30–60 s at all but their highest speeds. At each speed, subjects lowered themselves onto the treadmill by transferring their weight from the handrails while initiating the leg movements necessary to begin running on the moving treadmill belt. Subjects typically managed the transition to unassisted running in two to four steps after which force data were collected for a minimum of eight steps. Trials were considered successful if not more than 20 cm of forward or backward movement occurred during the eight steps. Top speeds were the last speeds successfully completed; multiple attempts were typically made at failure speeds. The greatest speeds achieved were within 0.2 m/s of the failure speed for all but three subjects. Level, declined, and inclined tests followed the same protocol.

Force applied to the running surface. The forces applied perpendicular to the running surface (F_{avge}/W_b and effective force) were measured using a treadmill-mounted force plate (18) with force signals amplified by a Vishay Instruments 2110 amplifier and recorded by a Macintosh computer at 1,000 Hz using custom-made LabView 4.0 software. Total stride times, swing times, contact times, and aerial times were determined from vertical force signals averaged over a minimum of eight steps (Fig. 1). The average mass-specific force ($F_{\text{avge}}/W_b = N/N_{W_b}$) applied during foot-ground contact to oppose gravity was determined from the ratio of step time to contact time. This measurement of support force, rather than the force-time integral, was used because the latter slightly underestimates the force applied normal to the

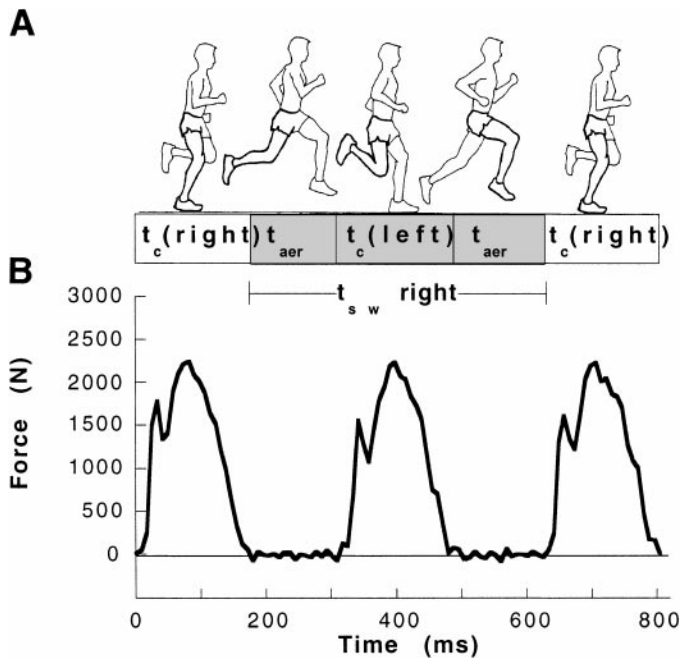


Fig. 1. Phases of a running stride (A) and simultaneous treadmill reaction force data (B) provided by the force plate for a representative runner. Force data were used to determine contact (t_c), aerial (t_{aer}), swing (t_{sw}), and total stride times (t_{str}). Note that the swing period is composed of two aerial periods and the intervening contact period of the contralateral limb.

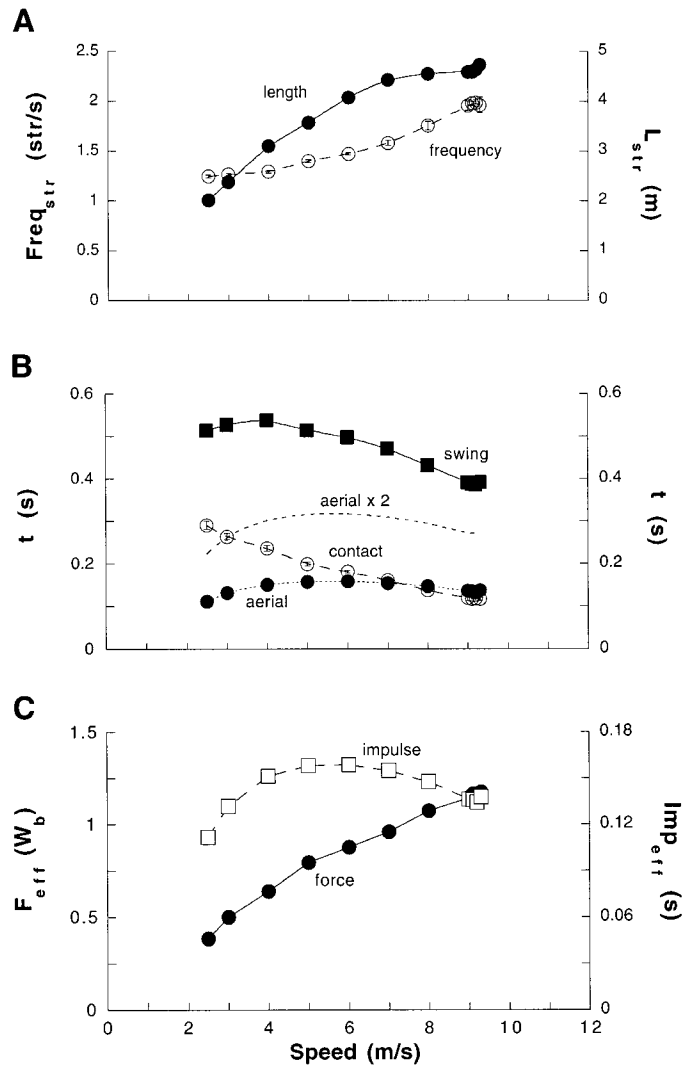


Fig. 2. Running mechanics as a function of speed for a representative subject. A: speed increases were achieved primarily by increasing stride lengths (L_{str}) at lower speeds and stride frequencies (Freq_{str}) at higher ones. B: stride frequency increases at higher speeds were due to reductions in both foot-ground contact times and swing times that together make up the total stride time. The aerial times comprising roughly two-thirds of the swing period (aerial \times 2) also decreased with increases in speed. C: effective support forces [$F_{\text{eff}} = (F - F_{W_b})/F_{W_b}$, where W_b is body weight] averaged over the period of foot-ground contact increased in direct proportion to running speed, whereas effective impulses ($\text{Imp}_{\text{eff}} = F_{\text{eff}} \cdot t_c$) increased from slower to intermediate speeds before decreasing to a minimum value at top speed. All values are means \pm SE for 1 subject. Error bars are obscured by all filled symbols and are too small to be visible for some variables.

ground during declined and inclined treadmill running. The force responsible for elevating the body against gravity and thus determining the body's aerial time (4), that exceeding the body's weight, or the effective force (F_{eff}), was determined from $(F - F_{W_b})/F_{W_b}$ (Fig. 2B). Thus $F_{\text{eff}} = F_{\text{avge}}/W_b - 1$.

Total stride time. Stride time (measured in s) was defined in accordance with Heglund et al. (12) as the time between consecutive footfalls of the same foot (Figs. 1 and 2B).

Step time. Step time (measured in s) was defined as the time between consecutive footfalls of opposite feet. Thus step time = stride time/2.

Contact time. Time of foot-ground contact (measured in s) was determined from the time the applied force exceeded 0 N on the force plate (Figs. 1 and 2B).

Aerial time. Aerial time (measured in s) was determined from the time between the end of the contact period of one foot and the beginning of the contact period of the opposite foot (Figs. 1 and 2B).

Swing time. Swing time (measured in s) was the time that a given foot was not in contact with the ground and was determined by subtracting the contact time from the total stride time (Figs. 1 and 2B).

Impulse applied to the running surface. Effective impulse values were determined from the product of the effective force applied to the running surface and foot-ground contact times. The forces applied to the running surface in opposition to gravity were normalized for the gravitational force exerted by the body's weight (F_{w_b}). Consequently, effective impulse values have units of seconds and provide the body's aerial time under conditions when the height of the center of mass above the running surface is the same on landing and takeoff (16, 20), a condition met on all three treadmill inclinations utilized here.

Stride frequency. Stride frequency (strides/s) was determined from the inverse of the total stride time (1/total stride time).

Step frequency. Step frequency (strides/s) was determined from the inverse of total step time; therefore, step frequency = stride frequency \cdot 2.

Stride length. Stride length (measured in m) corresponded to the belt distance traveled between successive contact periods of the same foot and was calculated by dividing the treadmill speed by stride frequency.

Step length. Step length (measured in m) corresponded to the belt distance traveled between successive contact periods of opposite feet. Thus step length = stride length/2.

Contact length. Contact length was determined from the product of foot-ground contact time and speed and thus provided the horizontal distance or length traveled by the belt during the contact period.

Video analysis. For general interest, we acquired swing time data from video for the first three finishers in the 100-m dash at the 1996 Olympics. These values are presented graphically but are not included in our statistical analysis. Swing times for the Olympic runners were determined by counting the number of video fields (NBC Sports, 60 fields/s) between right foot-up and right foot-down for eight consecutive strides beyond the 50-m mark. The average number of fields in eight swing periods was multiplied by the time per field to obtain each runner's swing time. Speeds were determined from the number of fields elapsing between each runner's crossing of the 50- and 100-m marks and the time per field. For laboratory subjects, we found that video contact time values exceeded simultaneously measured force plate contact time values by 15%, regardless of treadmill speed due to the brief intervals at the beginning and end of the contact period during which no force is applied to the belt. Thus we decreased the video contact time values of the Olympians by 15% to make the appropriate comparison to the force plate contact time values of our experimental subjects. This adjustment increased the video swing times of the Olympians only marginally (+4.6%).

Statistics

For the 33 subjects who completed the level treadmill test, swing times, contact times, aerial times, and the average mass-specific forces applied normal to the ground during

foot-ground contact were analyzed for significant differences as a function of top speed by simple linear regression ($P < 0.05$). The relative importance of step lengths, stride frequencies, and the average mass-specific force applied during foot-ground contact to top speed was assessed by the factorial change in each variable provided by the respective regression equation across the entire top speed range of the subjects tested. For the subjects who ran to top speed at -6° , 0° and $+9^\circ$ inclinations, top speeds, the average mass-specific forces applied to oppose gravity during foot-ground contact, swing times, contact times, aerial times, effective forces, and effective impulses were analyzed using a repeated-measures ANOVA with a Scheffé's test of post hoc means ($P = 0.05$).

RESULTS

Running Mechanics as a Function of Speed

Although sprinting abilities differed greatly among subjects and the top speeds of the same runners differed considerably on the different inclines, the mechanical means by which runners increased speed from a jog to top speed varied little (shown for a representative subject in Fig. 2). Across each individual's speed range, speed increases were achieved primarily by increasing stride lengths at lower speeds and stride frequencies at higher ones (Fig. 2A). The more rapid increases in stride frequency as subjects approached their top speeds were achieved through reductions in both the contact and swing times that make up the total stride time. Similarly, the time when neither foot was in contact with the ground (aerial time), which comprised most of the swing time at top speed (Fig. 2B), decreased as top speed was approached. These aerial time reductions resulted from decreases in effective impulse, the product of contact time and effective force, which determines the time a runner spends in the air (Ref. 4, Fig. 2, B and C). Reductions in vertical impulse as top speed was approached were due to decreases in the time of foot-ground contact that were larger than the increases in the effective force applied to the ground (Fig. 2, B and C).

Top Speed

Both experimental conditions provided the large differences in top speed necessary to provide rigorous hypothesis tests. For the 33 subjects who completed the level treadmill protocol, top speeds spanned a 1.8-fold range from 6.2 to 11.1 m/s (Fig. 3). For the five subjects who ran to top speed on different treadmill inclinations, mean top speeds spanned a 1.4-fold range between the declined and inclined conditions (Table 1).

Swing Times

The swing times of the 33 runners who completed the level protocol did not vary significantly in relation to their top running speeds (swing time = $0.42 - 0.0050x$, $R^2 = 0.06$, $P = 0.18$, mean = 0.373 ± 0.03 s, Fig. 3; x represents top speed in all regression equations). Similarly, the mean swing times of the five runners who ran to top speed on declined, inclined, and level treadmill gradients did not differ at top speed for

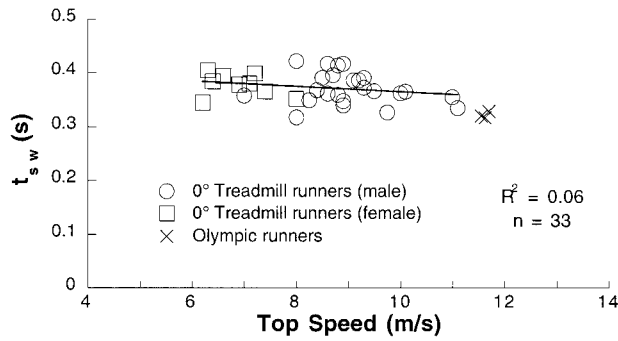


Fig. 3. t_{sw} vs. top running speed. Across a 1.8-fold range of top speeds, the minimum t_{sw} of different runners ($n = 33$) varied little (0.373 ± 0.03 s), being less than 0.03 s shorter for a runner with a top speed of 11.1 vs. 6.2 m/s. \times , First 3 finishers in the 100-m dash at the 1996 Olympics. Regression equations and R^2 values are for $n = 33$ treadmill subjects during level running in all figures ($t_{sw} = 0.42 - 0.0050x$, $R^2 = 0.06$, $P = 0.18$; x represents top speed in all equations).

two of the three conditions (Table 2). The only swing time means that differed significantly, those of declined vs. inclined running, varied by only 8%, with the briefer swing times occurring at the slower inclined top speeds.

For both fast and slow subjects during level running and the same runners on different inclinations, swing times decreased with increases in running speed to reach nearly the same minimum values at the top speed attained (Fig. 4).

Forces Applied to the Running Surface

The average mass-specific forces applied to oppose gravity during the period of foot-ground contact by our 33 runners at their top speeds during level treadmill running were significantly greater for faster runners compared with slower ones ($F_{ave}/W_b = 1.26 + 0.101x$, $R^2 = 0.39$, $P = 0.01$, Fig. 5A). This regression of F_{ave}/W_b on top speed indicated that, across the 1.8-fold range of top speeds measured, the average mass-specific force applied to the running surface increased 1.26 times. Similarly, the average mass-specific forces applied to the running surface at top speed to oppose gravity were greater during declined running vs. in-

Table 1. Contact lengths, step frequencies, and the average mass-specific support force applied to the running surface during the foot-ground contact period at top speed during declined, level, and inclined running

	L_c , m	Freq _{step} , steps/s	F_{ave}/W_b , N/N _{W_b}	Top Speed, m/s
Declined, -6°	0.99 ± 0.08*	4.38 ± 0.03	2.30 ± 0.06*†	9.96 ± 0.30*†
Level, 0°	0.99 ± 0.08*	4.38 ± 0.05	2.14 ± 0.08*	9.25 ± 0.37*
Inclined, +9°	0.92 ± 0.09	4.34 ± 0.08	1.76 ± 0.04	7.10 ± 0.31

Values are means ± SE for 5 subjects. Top speed is contact length (L_c) × step frequency (Freq_{step}) × the average mass-specific force applied to the running surface during the foot-ground contact period (F_{ave}/W_b , where W_b is body weight). *Significantly different from inclined running ($P < 0.05$). †Significantly different from level running ($P < 0.05$).

Table 2. Swing times, contact times, and stride times at top speed during declined, level, and inclined running

	t_{sw} , s	t_c , s	t_{str} , s
Declined, -6°	0.359 ± 0.004*	0.098 ± 0.003*†	0.457 ± 0.003
Level, 0°	0.350 ± 0.007	0.107 ± 0.003*	0.457 ± 0.005
Inclined, +9°	0.331 ± 0.005	0.130 ± 0.004	0.461 ± 0.009

Values are means ± SE for 5 subjects. Stride time (t_{str}) is swing time (t_{sw}) + contact time (t_c). *Significantly different from inclined running ($P < 0.05$). †Significantly different from level running ($P < 0.05$).

clined running by the equivalent of one-half of the body's weight (Table 1).

The time spent in the air (mean aerial time = 0.128 ± 0.004 s, Fig. 5C) at top speed did not vary as a function of the top speeds for our 33 subjects during level running. This was due to the equivalence of the vertical impulses determining aerial times among fast and slow runners. However, fast and slow runners achieved these equivalent impulses with different combinations of effective force and foot-ground contact times. Faster runners applied greater forces during briefer contact periods, whereas slower runners applied lesser ground forces during longer contact periods (Fig. 4, A and B). Aerial times and effective impulses at top speed were greater during declined (0.131 ± 0.01 s)

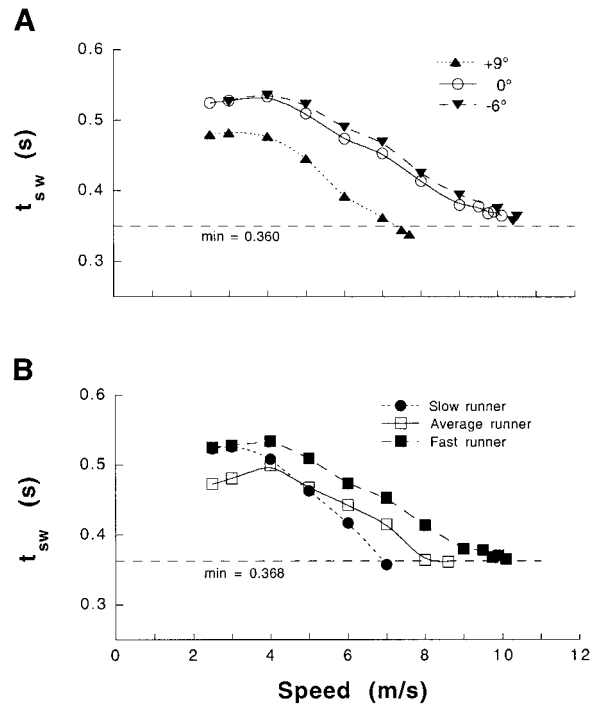


Fig. 4. t_{sw} as a function of running speed for individual runners. A: t_{sw} for a representative subject on inclined (+9°), level (0°), and declined (-6°) running surfaces decreased with increasing speed to reach similar minimum values at the different top speeds attained on the different inclinations. B: t_{sw} of slow, average, and fast subjects during level running also decreased with increasing speed, to reach similar minimum values at the considerably different top speeds of these individuals.

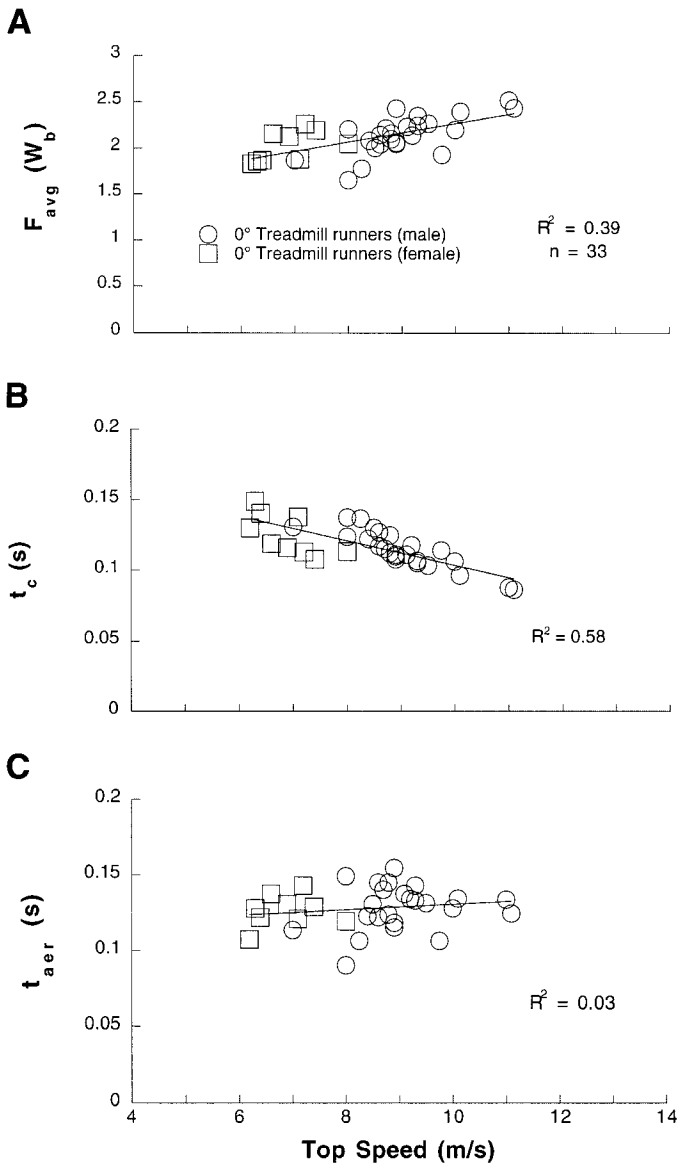


Fig. 5. Support force (F_{avg}/W_b), foot-ground t_c , and t_{aer} as a function of top running speed. A: average support forces of runners applied to the running surface (F/W_b) at top speed were systematically higher for faster runners, increasing 1.26 times across the 1.8-fold range of top speeds. The shorter t_c of faster runners (B) in combination with their higher ground forces resulted in equivalent impulses and t_{aer} among different runners at top speed (C). $F_{\text{avg}} = 1.26 + 0.101x$, $R^2 = 0.39$, $P = 0.02$; $t_c = 0.19 - 0.0087x$, $R^2 = 0.58$, $P = 0.01$; $t_{\text{aer}} = 0.11 + 0.0018x$, $R^2 = 0.028$, $P = 0.45$.

and lesser during inclined (0.100 ± 0.004 s) compared with level running (0.121 ± 0.004 s). This occurred because at the same running speed effective force was considerably higher during declined vs. inclined running, whereas foot-ground contact times were similar.

Stride Frequencies

Among the 33 runners who completed the level protocol, stride frequencies at top speed were significantly greater for faster runners (stride frequencies = $1.5 + 0.06x$, $R^2 = 0.30$, range = 1.8–2.4 strides/s), increasing

1.16-fold across the 1.8-fold range of top speeds. Mean stride frequencies at top speed during declined, level, and inclined running were virtually identical among the three conditions, being 2.19 ± 0.01 , 2.19 ± 0.02 , and 2.17 ± 0.04 strides/s, respectively. None of these means differed significantly.

Stride Lengths

The stride lengths at top speeds of the 33 runners completing the level protocol were significantly greater for faster than for slower runners (stride length = $1.03 + 0.37x$; $R^2 = 0.78$; range = 2.9–4.9 m). The regression of stride length on top speed indicated that the strides were 1.69 times longer for a runner with a top speed of 11.1 vs. 6.2 m/s. During declined, level, and inclined running, stride lengths were also closely related to the top speeds attained. Mean declined stride lengths of 4.6 ± 0.14 m were significantly greater than respective level means of 4.2 ± 0.17 m and declined means of 3.3 ± 0.10 m.

Contact Lengths

The contact lengths at top speed of the 33 runners completing the level protocol were significantly greater for faster than for slower runners (contact length = $0.68 + 0.015x$, $R^2 = 0.30$). However, within groups of men and women, contact lengths varied little to not at all in relation to top speed. On different surface inclinations, the contact lengths used at top speed did not differ between declined and level running but were significantly shorter during inclined running (Table 1).

DISCUSSION

We undertook this study to test the hypothesis that the different top speeds of human runners are determined by the amount of force applied to the ground rather than how rapidly limbs are repositioned in the air and found this to be the case in each of our two experimental tests. Both the greater top speeds of faster vs. slower level runners and those attained during declined vs. inclined running were achieved by the application of greater support forces to the ground while the legs were repositioned in nearly the same minimum time. Here, we also put forth a mechanical explanation for the limit to running speed with a more concrete physiological basis than the considerations of maximal stride lengths and frequencies that have typically framed this question. Because of the narrow constraints on the minimum swing times and maximum contact lengths that runners can use, speed is conferred predominantly by an enhanced ability to generate and transmit muscular force to the ground.

Hypothesis Test One: Comparing Faster and Slower Runners

Of the three mechanisms available to reach faster top speeds expressed in Eq. 5, we found that runners utilize stride frequency to a limited extent, support

forces predominantly, and contact lengths essentially not at all.

At top speed during level running, the regression equation for our 33 subjects indicated that stride frequency was 1.16 times greater for a runner with a top speed of 11.1 vs. 6.2 m/s. The relatively weak relationship between top speed and maximal stride frequency was the result of runners with different top speeds repositioning their swing legs in similar periods of time. Because the swing period comprises three-fourths of the total stride time at top speed, similarities in minimum swing times greatly minimized the extent of possible variation in maximal stride frequencies. Minimum swing times from our regression relationship (Fig. 3) were only 8% or three-hundredths of a second shorter for a runner with a top speed of 11.1 vs. 6.2 m/s. As an illustration of this result, our slowest subject, with a top speed of only 6.2 m/s, was able to reposition her leg for her next step nearly as rapidly as the fastest 100-m sprinter in the world (0.344 vs. 0.320 s) although she could only run half as fast. Despite the widespread belief to the contrary (11, 14, 15, 17, 30), a more rapid repositioning of limbs contributes little to the faster top speeds of swifter runners.

We found the second mechanical alternative for achieving faster top speeds, applying greater support forces to the ground, to be the predominant mechanism faster runners utilized to reach their faster top speeds. The regression of average mass-specific force applied to oppose gravity during the contact period on top speed indicated that this force was 1.26 times greater for a runner with a top speed of 11.1 vs. 6.2 m/s. Although support forces differed roughly twice as much across this range of top speeds as did either step frequencies or contact lengths, we expected these force differences to be greater. Our regression relationship indicates that altering the support force applied by only one-tenth of one body weight is sufficient to alter top speed by one full meter per second. In contrast, Eq. 5 predicts the force necessary to affect this difference in top speed should be twice this large for a runner with average step frequencies and contact lengths.

The large sensitivity of top speeds to small differences in the mass-specific support forces applied to the running surface resulted from the positive effect of support forces on maximal stride frequencies. Although we expected maximal stride lengths (Eq. 3) to be positively affected by support forces, we did not expect a positive effect on maximal stride frequencies also. Because both fast and slow runners required an aerial time of 0.128 s to achieve the minimum swing time required to reposition their legs for the next step, the modest differences in maximal stride frequencies between fast and slow runners resulted entirely from the contact portion of the stride being shorter in faster runners. For all runners on a level surface, aerial times are determined by the product of the effective force applied to the ground and the time of foot-ground contact. By applying greater support forces, faster runners were able to achieve the effective impulses and aerial times necessary to reposition their swing legs

with the shorter contact times that are used at higher speeds (Fig. 5). The briefer contact times made possible by the greater support forces applied by faster runners resulted in a positive relationship to maximal stride frequencies ($R^2 = 0.30$; $P = 0.001$). Thus the sensitivity of top speeds to the forces applied to the running surface resulted from the positive effect support forces had on both the maximal stride lengths and frequencies that runners were able to attain.

We found little difference in the third mechanism that would enable faster runners to reach faster top speeds: increasing the forward distance traveled during the stance period or contact lengths. Our regression equation indicated that contact lengths were 1.10 times greater for a runner with a top speed of 11.1 vs. 6.2 m/s. However, this resulted from a gender difference in top speed: our female subjects generally had shorter legs, shorter contact lengths, and slower top speeds. Within groups of male and female runners, contact lengths varied little or not at all in relation to top speed. Although elongated steps would provide a speed advantage by increasing the time available to apply ground force, runners do not exercise this option because unnaturally long steps compromise the ability of the active muscles to apply the ground force necessary to elevate the body for the ensuing step. By worsening the mechanical advantage and disrupting the natural spring-like behavior of the leg (8), unnaturally elongated steps increase the muscle forces and volumes that must be recruited per unit of force applied to the ground (22). Reductions in the ground force applied in relation to the muscle forces generated would directly reduce maximum ground forces and therefore also reduce top running speeds.

Hypothesis Test Two: Comparing Declined and Inclined Running

The results of our second test indicated that the amount of force applied to the running surface was the most important determinant of the greater top speeds attained during declined vs. inclined running. Contact lengths contributed only modestly to top speed differences under these conditions, and maximal stride frequencies did not contribute at all.

Although equivalent maximal stride frequencies do not explain the different top speeds achieved during declined and inclined running, they do provide additional evidence that a constraint on minimum swing times limits the top speeds of human runners. The means for minimum swing times at top speed on the different inclinations varied little and were virtually the same as those of fast and slow runners during level running (Fig. 3, Table 2). Although declined top speeds exceeded inclined top speeds by 41%, minimum swing times differed by only 8% and were actually shorter for the slower inclined condition. We attributed the slightly shorter and longer minimum swing times during declined and inclined running, respectively, to the running surface interrupting the limb's arc slightly later and earlier under these respective conditions

rather than to differences in the velocity at which the limb was repositioned for the next step.

The small portion of the difference in the top speed means not explained by the average mass-specific force applied to the running surface to oppose gravity resulted from the longer contact lengths used during declined vs. inclined running (Table 1). Contact lengths that were 0.07 m longer at top speed during declined vs. inclined running provided an additional speed of 0.72 m/s or 25% of the top speed difference between conditions. Although contact lengths generally do not vary on different inclinations at the same slow and intermediate running speeds (16, 23), our data indicate runners do use slightly shorter contact lengths at faster speeds. The occurrence of contact length adjustments at only the highest inclined speeds may result from the need to modify the position of the limb to provide greater mechanical power to elevate the body more rapidly against gravity.

The application of mass-specific forces that were greater by one-half of the body's weight during declined vs. inclined running conferred an additional 2.1 m/s to the top speeds attained on the declined surface or 75% of the total difference between conditions (Table 1). Although faster declined vs. inclined top speeds were certainly expected, our data indicate that this single mechanical variable accounts for the large majority of these intuitive performance differences. Furthermore, the different maximum support forces that the limbs can apply to the running surface on different inclinations appear to be directly explained by the force-velocity properties of skeletal muscle. Both direct evidence (27) and indirect evidence (3) indicate that the mechanical activity of the extensor muscles that apply ground force during the stance phase is biased toward lengthening contractions that produce greater forces during declined running and shortening contractions that produce lesser forces during inclined running (15). The relationship between the forces generated by the extensor muscles and those that the limb applies to the ground appears to vary little on different inclinations (T. J. Roberts, personal communication). Thus the differences in the speed capabilities of runners on different inclinations are due largely to the influence of the force-velocity properties of muscle on the maximum forces the limbs can apply to the ground.

General Implications From Both Tests: What Limits Running Speed?

We believe the consistency of the relationships between support forces, aerial times, effective impulses, and swing times under the different experimental conditions link the mechanics of the ground force application to minimum swing times to explain the mechanical limit to running speed. Although the support forces applied to the running surface increased with increasing speed and reached individual maximums at the top speeds of different runners, the relatively larger reductions in foot-ground contact times that accompanied the greater support forces applied at faster running

speeds resulted in reductions in both the aerial and swing periods of the stride. In each case, top speed was reached when increases in speed and decreases in foot-ground contact times reduced effective impulses and aerial times to the minimum values providing sufficient time to swing the leg into position for the next step (Fig. 2). These speeds were greater during declined vs. inclined running and for faster vs. slower level runners because greater support forces allowed the necessary impulses and aerial times to be provided with shorter contact times and therefore at higher speeds.

In addition to advancing the understanding of human speed, our results offer a more general and unexpected link between the physiological features of swift runners and the mechanical basis of their higher speeds. Certainly, top sprinters have faster muscle fibers and greater muscular power available to reposition their limbs (7, 11, 14, 15) yet do so little or no faster than average and slow human runners do. From this result, we infer that faster fiber speeds do not allow legs to be repositioned appreciably faster. Although the activation of the flexor muscles and tendons that reposition the limb during the swing period is considerable at high speeds (1), this activation likely occurs to increase the storage and release of mechanical energy in the oscillating limb rather than to generate mechanical power chemically within these muscles. Similar patterns of flexor activation during high-speed running in other species suggest that rapid limb repositioning is achieved similarly (10, 26) and that minimum swing times limit the top speeds of running animals. Accordingly, we suggest that the mechanism by which faster muscle fibers confer faster top running speeds in terrestrial cursors is not by decreasing minimum swing times but by increasing the maximum rates at which force can be applied to the ground.

We conclude that human runners reach faster top speeds not by repositioning their limbs more rapidly in the air but by applying greater support forces to the ground.

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