Interaction of Step Length and Step Rate during Sprint Running

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ABSTRACT

HUNTER, J. P., R. N. MARSHALL, and P. J. MCNAIR. Interaction of Step Length and Step Rate during Sprint Running. *Med. Sci. Sports Exerc.*, Vol. 36, No. 2, pp. 261–271, 2004. A "negative interaction" between step length and step rate refers to an increase in one factor resulting in a decrease in the other. **Purposes**: There were three main purposes: a) to investigate the relative influence of the determinants of step length and step rate, b) to determine the sources of negative interaction between step length and step rate, and c) to investigate the effects of manipulation of this interaction. **Methods:** Thirty-six athletes performed maximal-effort sprints. Video and ground reaction force data were collected at the 16-m mark. Sprint velocity, step length, step rate, and their underlying determinants were calculated. Analyses included correlations, multiple linear regressions, paired *t*-tests, and a simple simulation based on alterations in flight determining parameters. **Results:** A wide range of step length and step rate combinations was evident, even for subgroups of athletes with similar sprint velocities. This was partly due to a negative interaction that existed between step length and step rate; that is, those athletes who used a longer step length tended to have a lower step rate and *vice versa*. Vertical velocity of takeoff was the most prominent source of the negative interaction. **Conclusions:** Leg length, height of takeoff, and vertical velocity of takeoff are all possible sources of a negative interaction between step length and step rate. The very high step lengths and step rates achieved by elite sprinters may be possible only by a technique that involves a high horizontal and low vertical velocity of takeoff. However, a greater vertical velocity of takeoff might be of advantage when an athlete is fatigued and struggling to maintain a high step rate. **Key Words:** STRIDE LENGTH, STRIDE RATE, NEGATIVE INTERACTION, GROUND REACTION IMPULSE

Sprint running horizontal velocity is the product of step length and step rate. (In this article we have used the term "step" to define half a running cycle, that is, from foot contact to the next contact of the opposite foot. The term "stride," therefore, defines a complete cycle, from foot contact to the next contact of that same foot (3).) Accordingly, an increase in one factor will result in an improvement in sprint velocity, as long as the other factor does not undergo a proportionately similar or larger decrease. From this point forward, we will refer to the negative effect that an increase in step length might have on step rate, and *vice versa*, as a "negative interaction." This negative interaction has previously been discussed (9,14) but has not been researched directly. In particular, the sources of the negative interaction, and the relative influence of these sources are currently not well defined.

Research investigating the relative importance of developing a long step length or high step rate has been inconclusive. Step rate (18,20) and related aspects (25,28) have been proposed as the speed limiting factors in sprint running; however, some researchers (1) have suggested that a long step length is more important. Other researchers (14,17) have supported the need to develop a greater step length *and* step rate. Despite these varying opinions, the possibility of a negative interaction between step length and step rate should be considered when training an athlete to increase step length, step rate, or both.

In determining the sources of the negative interaction, it would be helpful to consider what determines step length and step rate. Hay (9) has provided much insight into this area with his discussion based on a "deterministic model." Figures 1 and 2 are adaptations of Hay's model, and show step length and step rate divided into subcomponents such as stance distance, flight distance, stance time, and flight time. The models then specify the determinants of these subcomponents. The relative influ-

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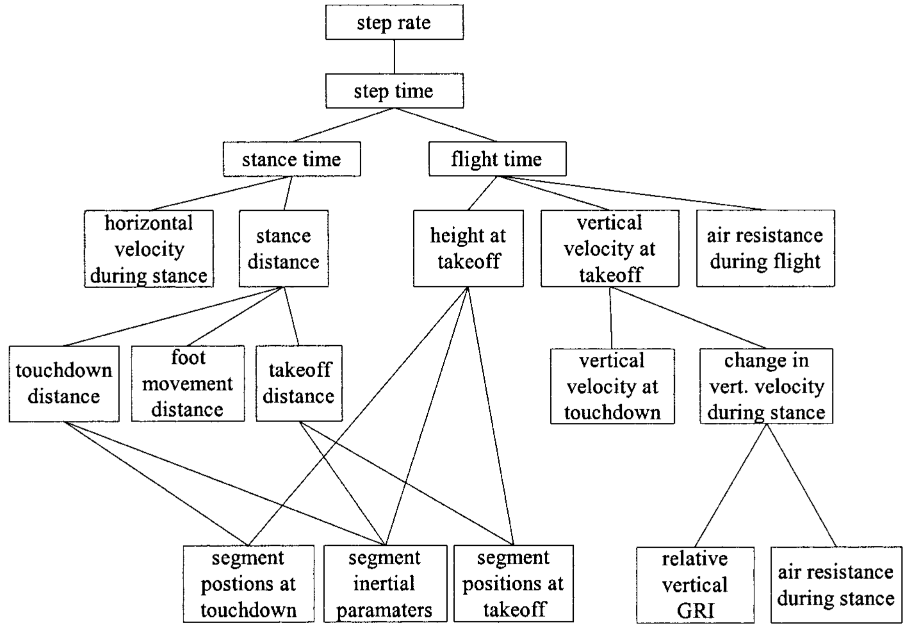

FIGURE 1—Determinants of step rate (adapted from Hay (9)).

ence of many of these determinants is unknown, and therefore, requires investigation.

Knowledge of the relative influence of the determinants in Figures 1 and 2 would be of great value to coaches when training an athlete to increase step length or step rate. Furthermore, in such a situation, it is also important to know how an improvement in one factor (i.e., step length or step rate) will likely affect the other. Subsequently, there were three main purposes to this study: a) to investigate the relative influence of the determinants of step length and step rate (as based on Figs. 1 and 2), b) to determine the likely sources of the negative interaction between step length and step rate, and c) to investigate the effects of manipulation of this interaction. Each of these three purposes is assessed in Parts I, II, and III of this article.

METHODS

Subjects. All subjects involved in this research participated in sports involving sprint running (e.g., athletics, soccer, touch rugby, etc.). Part I of this research involved 28 male athletes with a mean ± SD for age, height, and body mass of 22 ± 4 yr, 1.77 ± 0.06 m, and 74 ± 6 kg, respectively. Part II included a total subject pool of 36 athletes (31 males and 5 females) who were paired according to the following criteria: gender, similar mean sprint velocity during the step from the force plate (difference of no greater than 0.05 $m \cdot s^{-1}$), similar leg length (difference of no greater than 6.0 cm), and notably different step rate (difference of at least 0.15 Hz). Eight pairs (seven pairs of males and one pair of females) fit these criteria. Mean ± SD

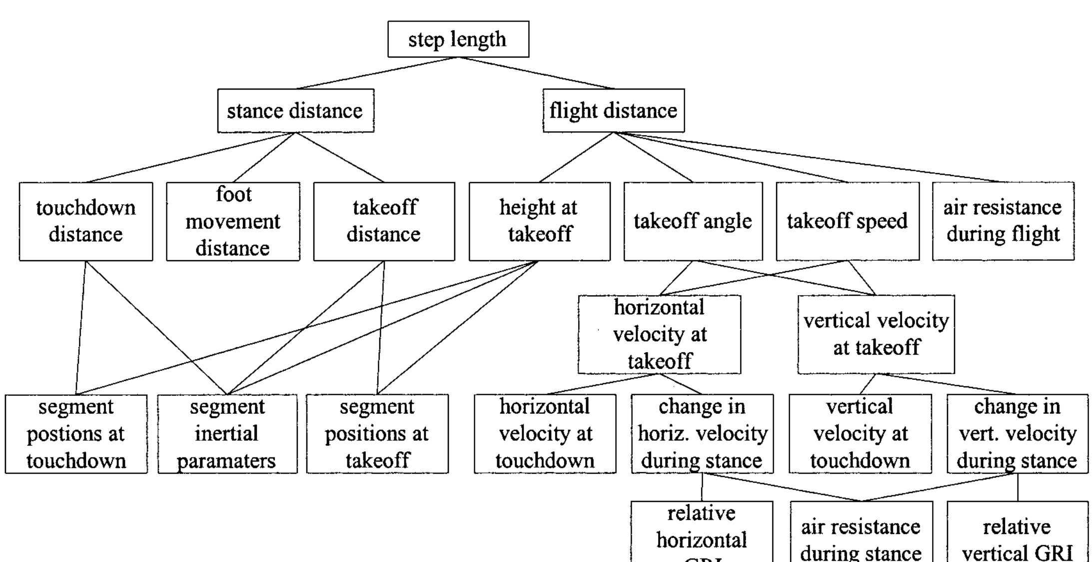

FIGURE 2—Determinants of step length (adapted from Hay (9)).

TABLE 1. Description of marker placement.

Marker	Position
Forefoot	On top of the second metatarsal, approximately 2.0 cm posterior from its head.
Medial toe*	On the medial side of the base of the big toe, so a line intersecting with the centroid of the marker and the head of the second metatarsal is perpendicular to the long axis of the foot.
Heel	On the most posterior surface of the calcaneous, approximately 2.0 cm above ground level when the subject is standing stationary.
Lateral ankle	On the lateral malleolus, immediately superior (≈5mm) to its distal tip.
Medial ankle*	The distal tip of the medial malleolus.
Mid-shank	Approximately halfway up the anterior surface of the shank.
Lateral knee	On the maximal protrusion of the lateral epicondyle, approximately at the level of the lower third of the patella, when the knee is extended.
Medial knee*	On the maximal protrusion of the medial epicondyle, approximately at the level of the lower third of the patella, when the knee is extended.
ASIS	Anterior superior iliac spine.
Mid-PSIS	Mid-way between the posterior superior iliac spines.
Greater trochanter*	The most lateral protrusion of the greater trochanter.
Cervical vertebrae	On the posterior spinous process of the seventh cervical vertebrae.
Suprasternal notch	On the front of the neck, one centimeter above the supra-sternal notch.
Shoulder	With the subject's upper-arm hanging freely, the marker is placed over the glenohumeral joint center when viewed in the sagittal plane.
Vertex	On the most superior point of the head.
Elbow	With the subject's elbow flexed to 90° in the sagittal plane, the marker is placed over the estimated elbow joint center when viewed in the sagittal plane.
Wrist	With the subject's hand in a pronated position, the marker is placed on top of the wrist over the estimated joint center.

All markers, except mid-PSIS, cervical vertebrae, suprasternal notch, and vertex, were on the left and right sides of the body. An asterisk indicates the markers that were removed after the static trial. To ensure a dislodged marker could be replaced precisely in its original location, marker positions were traced on the skin with ink. Pelvic and hip marker positions were based on a method proposed by Bell et al. (2) knee and ankle marker positions were based on information provided by Zatsiorsky (30) and de Leva (6).

of these 16 subjects for age, height, and body mass were 24 ± 5 yr, 1.76 ± 0.08 m, and 73 ± 9 kg, respectively. Part III involved a simple simulation in which the mean data of the athletes in Part I were used. Approval to undertake the study was given by The University of Auckland Human Subjects Ethics Committee. Written informed consent was obtained from each athlete.

Data collection. The athletes performed maximal-effort sprints on a synthetic track that passed through the laboratory. Three-dimensional kinematic data were obtained at a sampling rate of 240 Hz from eight Falcon High Resolution Cameras and EVa 6.15 data collection system (Motion Analysis Corporation, Santa Rosa, CA). The video capture volume was approximately 6.0 m long, 2.4 m high, and 2.0 m wide and was centered 16 m from the sprint start line. Video calibration was performed at the beginning of each data collection session. A recessed force-plate (Bertec 6090s; Bertec Corporation, Columbus, OH) located 16 m from the sprint start line was used to measure ground reaction force (GRF). The force plate's signals were amplified (Bertec AM6-3 amplifier) and recorded in EVa 6.15 at a sampling rate of 960 Hz. A matrix provided by the manufacturers, and checked for accuracy by the experimenters, was used for force calibration. A manual trigger simultaneously initiated video and force plate data collection.

The testing session began with the athlete performing a general warm-up of choice. After this, markers were attached (see Table 1) and a static trial, in which the subject stood stationary, was collected. Next, eight markers were removed (see Table 1), and after an additional warm-up, the athlete performed maximal-effort sprints, 25 m in length, from a standing start. The rest period between sprints typically lasted about 4 min. Successful trials were those that the athlete clearly contacted the force plate without adjusting his or her natural running pattern. So that this could occur, the sprint start line was adjusted by no more than 1 m. Generally, each athlete performed seven or eight sprints, 25 m in length, which typically resulted in four or five successful trials. During data collection the athlete wore a cropped vest, shorts and spiked track shoes.

Data treatment. The human body was modeled as 12 rigid segments articulating at joints with fixed centers of rotation. The segments included: trunk (from mid-hips to base of the neck), head (including neck), upper arms, lower arms (including hands), thighs, shanks, and feet. All segments, with the exceptions of the upper and lower arms, were modeled as internal links (i.e., within the body). This required calculation of internal segment endpoints for the following: head of the second metatarsal of the foot, ankle joint center, knee joint center, hip joint center, mid-hips, and neck. The vertex of the head, the shoulder, elbow, and wrist endpoints were all based on external markers. Segment inertia parameters were obtained from de Leva (5), with the exception of the foot's center of mass location which was obtained from Winter (27). The mass of the shoe (typically ~200 g) was added to the mass of the foot.

From the static trial data, the neck endpoint was calculated as halfway between the suprasternal notch and cervical vertebrae markers, the hip joint center was calculated using the hybrid method proposed by Bell et al.(2), the mid-hips endpoint was calculated as halfway between the two hip joint centers, knee and ankle joint centers were calculated as halfway between the lateral and medial markers of the respective joint, and the head of the second metatarsal was calculated as the point where a line through the medial toe marker and perpendicular to the long axis of the foot, intersected with a plane containing the heel marker, forefoot marker, and ankle joint center. The position of each internal joint center was measured relative to a group of three reference markers located on an adjacent segment. It was assumed that throughout the testing session the three markers within each group remained in fixed positions relative to one another. For the sprint trial data (during which a limited marker set was worn; see Table 1), joint centers were calculated via knowledge of their relative positions.

From the collected three-dimensional data, two-dimensional sagittal plane coordinates were extracted and used for further analysis. The data were smoothed with a fourth-order, low-pass Butterworth filter (27). A cutoff frequency for each X and Y component of each joint trajectory was determined subjectively after viewing the raw and filtered acceleration data of five athletes. Once decided upon, the same cutoff frequencies (ranging from 7 to 12 Hz) were used for all athletes. GRF data were filtered with a cutoff frequency of 75 Hz.

The instants of touchdown and takeoff from the force plate were defined as when the vertical GRF first rose above 10 N (touchdown) and reduced to 25 N (takeoff). The instant of touchdown for the first ground contact beyond the force plate was assumed to occur at the instant of peak vertical acceleration of the head of second metatarsal (12). This method, we found, predicted the exact frame of touchdown, or 1 frame late (0.004 s), 93% of the time.

Twenty-three variables based on Figures 1 and 2 were calculated:

Angle of takeoff: the angle, measured relative to horizontal, of the velocity vector of the center of mass of the body (COM) at takeoff.

Flight distance: the horizontal distance the COM traveled during the flight phases.

Flight time: duration of the flight phase.

Foot movement distance: the horizontal distance the head of the second metatarsal of the stance foot moved during the stance phase.

Height of takeoff: the difference between the height of COM at takeoff and the height of COM at the following touchdown.

Horizontal velocity during stance: mean horizontal velocity of COM during the stance phase.

Horizontal velocity of touchdown and takeoff: horizontal velocity of COM at touchdown and takeoff from the force plate.

Leg angle at touchdown and takeoff: the acute angle measured between horizontal and a line passing through the stance ankle and the COM, at the moments of touchdown and takeoff. These angles were used as measures of "segment positions" at "touchdown" and "takeoff" as listed in Figures 1 and 2.

Leg angle range-of-motion: the angular range of motion, during stance, of the line passing through the stance ankle and COM. The sum of the leg angle at touchdown, leg angle range-of-motion, and leg angle at takeoff equals 180°.

Relative horizontal GRI: net horizontal (fore-aft) ground reaction impulse expressed relative to body mass. The units are meters per second and reflect the change in horizontal velocity of COM during the stance phase (ignoring horizontal air resistance).

Relative vertical GRI: vertical ground reaction impulse less body weight impulse, then expressed relative to body mass. The units are meters per second and reflect the change in vertical velocity of COM during the stance phase (ignoring vertical air resistance).

Speed of takeoff: the magnitude of the resultant velocity of COM at takeoff.

Sprint velocity: mean horizontal velocity of COM during the step from the force plate.

Stance distance: the horizontal distance the COM traveled during the stance phase.

Stance time: duration of the stance phase.

Step length: horizontal distance between the point of touchdown of one foot (head of second metatarsals) to that of the following touchdown for the opposite foot.

Step rate: steps taken per second.

Takeoff distance: horizontal distance from the head of the second metatarsals of the stance foot to the COM, at the moment of takeoff.

Touchdown distance: horizontal distance from the head of the second metatarsals of the stance foot to the COM, at the moment of touchdown.

Vertical velocity of touchdown and takeoff: horizontal and vertical velocity of COM at touchdown and takeoff from the force plate.

Data analysis. In all cases (with one exception, which is explained in the latter part of the next paragraph), the data used for analysis were the means from the fastest three trials of each athlete. The data were analyzed in three parts.

Part I involved Pearson correlations and "standard" multiple linear regressions (based on Figs. 1 and 2) to investigate the "relative influence" of the determinants of step length, step rate, stance time, stance distance, flight time, and flight distance, for the group of 28 male sprinters. In addition, to investigate whether, on a within-subject basis, the athletes achieved their fastest trial with a greater step length or step rate, a paired *t*-test was used to test for a difference in step rate, and also step length, between the fastest and third fastest trial each athlete.

Part II investigated the possible sources of the negative interaction between step length and step rate. From a total subject pool of 36 athletes, eight "matched pairs" were formed, based on close similarities in sprint velocity and leg length, same gender, but notable differences in step rate and step length. That is, each pair had almost identical sprint velocity but produced this velocity with markedly different technique (i.e., step rate and step length combination). From each pair, one subject was put into the "high step rate group," and the other into the "long step length group." It was assumed that the group differences in step rate and step length would be due, at least in part, to the "negative interaction" discussed earlier. To find the possible sources of this interaction, paired *t*-tests were used to detect differences in the determinants of step rate and step length.

Part III investigated the effects of manipulation of the negative interaction between step length and step rate. The mean data of the 28 male athletes in Part I were used as input into a simple simulation that predicted step length, step rate, and sprint velocity from stance distance, stance time, and three flight determining parameters: horizontal velocity of takeoff, vertical velocity of takeoff, and height of takeoff. Sprint velocity (SV) is the product of step length (SL) and

TABLE 2. Multiple regressions to predict stance time, stance distance, flight time, and flight distance.

Prediction of Stance Time

Predictors: v_s, mean horizontal velocity during stance ($m \cdot s^{-1}$); θ_{td}, leg angle at touchdown (deg); θ_{to}, leg angle at takeoff (°); len, leg length (m)

Prediction equation: stance time (ms) $= 336.3 - 9.2 \cdot v_s - 1.3 \cdot \theta_{td} - 2.0 \cdot \theta_{to} + 72.1 \cdot len$

Prediction strength: $R^2 = 0.88$**; adjusted $R^2 = 0.86$**

	Regression Parameters			Pearson Correlations (r)			
	β	r^2	sr^2	Stance Time	Horizontal Velocity	Leg Angle at TD	Leg Angle at TO
Horizontal velocity	−0.38**	0.23*	0.07**	−0.48*			
Leg angle at touchdown	−0.41**	0.59**	0.07**	−0.77**	0.63**		
Leg angle at takeoff	−0.54**	0.40**	0.18**	−0.63**	−0.05	0.43*	
Leg length	0.41**	0.01	0.15**	0.10	0.33	0.26	0.15

Prediction of Stance Distance

Predictors: θ_{td}, leg angle at touchdown (°); θ_{to}, leg angle at takeoff (°); len, leg length (m)

Prediction equation: stance distance (m) $= 1.874 - 0.007 \cdot \theta_{td} - 0.018 \cdot \theta_{to} + 0.625 \cdot len$

Prediction strength: $R^2 = 0.81$**; adjusted $R^2 = 0.79$**

	Regression Parameters			Pearson Correlations (r)		
	β	r^2	sr^2	Stance Distance	Leg Angle at TD	Leg Angle at TO
Leg angle at touchdown	−0.32**	0.22*	0.08**	−0.47*		
Leg angle at takeoff	−0.68**	0.54**	0.38**	−0.74**	0.43*	
Leg length	0.50**	0.10	0.23**	0.32	0.26	0.15

Prediction of Flight Time

Predictors: h, height of takeoff (m); v_v, vertical velocity of takeoff ($m \cdot s^{-1}$)

Prediction equation: flight time (ms) $= 17.2 + 1303.4 \cdot h + 158.5 \cdot v_v$

Prediction strength: $R^2 = 0.85$**; adjusted $R^2 = 0.83$**

	Regression Parameters			Pearson Correlations (r)	
	β	r^2	sr^2	Flight Time	Height
Height of takeoff	0.59**	0.13	0.32**	0.36	
Vertical velocity	0.88**	0.52**	0.72**	0.72**	−0.26

Prediction of Flight Distance

Predictors: h, height of takeoff (m); v_v, vertical velocity of takeoff ($m \cdot s^{-1}$); v_h, horizontal velocity of takeoff ($m \cdot s^{-1}$)

Prediction equation: flight distance (m) $= -0.830 + 10.837 \cdot h + 1.322 \cdot v_v + 0.117 \cdot v_h$

Prediction strength: $R^2 = 0.88$**; adjusted $R^2 = 0.87$**

	Regression Parameters			Pearson Correlations (r)		
	β	r^2	sr^2	Flight Distance	Height	Vertical Velocity
Height of takeoff	0.50**	0.18*	0.19**	0.42*		
Vertical velocity	0.75**	0.43**	0.49**	0.65**	−0.26	
Horizontal velocity	0.32**	0.35**	0.08**	0.59**	0.36	0.12

* $P < 0.05$, ** $P < 0.01$. The beta values (β) are the standardized regression coefficients and can be used to estimate the relative influence of each predictor variable on the dependent variable, if the predictor variables are unrelated. The Pearson correlations (r) are used to assess the interrelationship of the predictor variables, and also the relationship of each individual predictor variable with the dependent variable. A squared Pearson correlation (r^2) reflects the variance in the dependent variable that is explained by a predictor variable, but not necessarily exclusive to that predictor variable (i.e., some of that explained variance could possibly also be explained by other predictor variables). In contrast, a squared semi-partial correlation (sr^2) reflects the variance in the dependent variable that is explained by, and exclusive to, a predictor variable. All these figures should be considered when attempting to determine the relative influence of the predictor variables on the dependent variable (24).

step rate (SR). Step length and step rate can also be expressed as the sum of their components, which gives

$$SV = SL \cdot SR = (D_{stance} + D_{flight}) \cdot (T_{stance} + T_{flight})^{-1},$$

where D_{stance}, D_{flight}, T_{stance}, and T_{flight} are the stance distance, flight distance, stance time, and flight time, respectively. The group-mean values of stance distance and stance time were used as input into the above equation. The values for flight distance and flight time, however, were calculated from the group-mean values for horizontal velocity, vertical velocity, and height of takeoff. This was done using two different methods: a) using the flight distance and flight time regression equations of Part I (see Table 2) and b) using "projectile equations" that predict the flight distance and flight time of a projectile (9). The latter of these methods involved calculating the angle of takeoff (θ) and magnitude of the resultant velocity of takeoff (v) by using $\theta = tan^{-1}(v_v/v_h)$ and $v = (v_v^2 + v_h^2)^{0.5}$, where v_v and v_h are the vertical and horizontal velocity of takeoff, respectively. Flight distance and flight time were then calculated using projectile equations

$$T_{flight} = [v \cdot sin\theta + ((v \cdot sin\theta)^2 + 2 \cdot g \cdot h)^{0.5}]/g$$

and

$$D_{flight} = [v^2 \cdot sin\theta \cdot cos\theta + v \cdot cos\theta \cdot ((v \cdot sin\theta)^2 + 2 \cdot g \cdot h)^{0.5}]/g,$$

where g is a gravitational constant ($9.81\ m \cdot s^{-2}$), h is the height of takeoff (i.e., the height of the COM at takeoff less the height of the COM at the subsequent touchdown), and θ is the angle of takeoff (in radians). The entire procedure described above was repeated with small changes made to horizontal velocity, vertical velocity, angle, or height of takeoff. It was assumed that for small changes in the flight determining parameters, stance time and distance would

TABLE 3. Determinants of sprint velocity, step length, and step rate for the high step rate group and long step length group. For comparison, data for the fastest and slowest of the 28 male athletes in Part I have been included.

	High Step Rate Group	Long Step Length Group	Fastest Individual	Slowest Individual
Anthropometry				
Body height (m)	1.74 ± 0.09	1.77 ± 0.08	1.79	1.68
Leg length (m)	0.93 ± 0.05	0.93 ± 0.04	0.94	0.89
Body mass (kg)	72.1 ± 10.3	73.1 ± 7.8	71.8	70.7
Sprint Performance				
Sprint velocity (m·s^{-1})	8.08 ± 0.45	8.09 ± 0.45	8.80	7.44
**Step rate (Hz)	4.41 ± 0.26	4.11 ± 0.27	4.45	4.44
**Step length (m)	1.84 ± 0.11	1.97 ± 0.11	1.98	1.68
Step				
Determinants of step length				
Stance distance (m)	0.98 ± 0.06	0.96 ± 0.06	0.95	0.86
**Flight distance (m)	0.86 ± 0.08	1.01 ± 0.13	1.00	0.78
Determinants of step rate				
Stance time (ms)	125 ± 10	124 ± 13	111	117
**Flight time (ms)	102 ± 10	121 ± 14	114	109
Flight				
Determinants of flight distance				
Height of takeoff (cm)	1.3 ± 0.5	1.6 ± 0.6	2.4	1.6
*Angle of takeoff (°)	3.2 ± 0.5	3.7 ± 0.7	2.6	3.1
Speed of takeoff (m·s^{-1})	8.20 ± 0.44	8.21 ± 0.46	8.92	7.60
Horizontal velocity at takeoff (m·s^{-1})	8.19 ± 0.44	8.20 ± 0.46	8.91	7.59
*Vertical velocity at takeoff (m·s^{-1})	0.46 ± 0.06	0.53 ± 0.10	0.41	0.42
Determinants of flight duration				
Height of takeoff (cm)	See above			
*Vertical velocity at takeoff (m·s^{-1})	See above			
Stance				
Determinants of stance distance				
Touchdown distance (m)	0.28 ± 0.04	0.27 ± 0.04	0.19	0.25
Foot movement distance (m)	0.05 ± 0.01	0.06 ± 0.02	0.08	0.05
Takeoff distance (m)	0.65 ± 0.05	0.63 ± 0.04	0.69	0.56
Leg angle at touchdown (°)	80 ± 2	80 ± 3	84	80
Leg angle at range-of-motion (°)	50 ± 2	48 ± 4	44	46
Leg angle at takeoff (°)	50 ± 2	52 ± 2	52	54
Leg length (m)	See above			
Determinants of stance time				
Horizontal velocity during stance (m·s^{-1})	7.99 ± 0.46	7.98 ± 0.43	8.68	7.31
Stance distance (m)	See above			
Takeoff Velocity				
Determinants of horizontal velocity at takeoff				
Horizontal velocity at touchdown (m·s^{-1})	8.03 ± 0.40	8.01 ± 0.44	8.62	7.44
Change in horizontal velocity, during stance	See footnote			
Relative horizontal GRI (m·s^{-1})	0.23 ± 0.06	0.25 ± 0.03	0.35	0.19
Determinants of vertical velocity at takeoff				
Vertical velocity at touchdown (m·s^{-1})	−0.70 ± 0.08	−0.74 ± 0.08	−0.80	−0.66
Change in vertical velocity during stance	See footnote			
*Relative vertical GRI (m·s^{-1})	0.95 ± 0.11	1.08 ± 0.14	1.03	0.92

Figures for the groups are mean ± standard deviation. Statistically significant differences between the high step rate and long step length groups are indicated with $*P < 0.05$; $**P < 0.01$. Changes in velocity during stance are not presented in the table; however, relative vertical and horizontal ground reaction impulse (GRI) would be identical to these changes apart from the effects of air resistance.

remain constant. This procedure allowed us to predict the effects a small change in each of the flight determining parameters would have on step length, step rate, and sprint velocity.

To maintain an acceptable level of statistical power, each statistical test was conducted with an alpha level of 0.05. The number of tests that would be likely to return a significant result by chance alone (Type 1 error) can be calculated by multiplying the alpha level by the total number of tests conducted. In Part I, 50 statistical tests were conducted and 35 returned a significant result, however, about three of these (i.e., 0.05·50) would likely have occurred by chance alone. In Table 3 of Part II, 26 statistical tests were conducted and seven returned significant results; however, about 1 of these (i.e., 0.05·26) would likely have occurred by chance alone.

All sample size estimations were based on an alpha level of 0.05. The 28 subjects in Part I provided 80% power in detecting a correlation of 0.50 (4) and exceeded the minimum required "subject to predictor-variable ratio" of 5 to 1 for "standard" multiple linear regression, recommended by Hair et al. (7). With regards to Part II, *post hoc* calculations revealed that, for almost all variables, eight pairs of subjects provided at least 70% power in detecting an effect size of 1.0 (4).

RESULTS

Figure 3 shows, for all 36 athletes tested, a "bubble plot" of step length, step rate, and sprint velocity. A wide variety of step length and step rate combinations were used, even for the fastest six athletes (see the black bubbles) who had sprint velocities ranging from 8.63 to 8.80 m·s^{-1}.

Part I: the relative influence of determinants of step length and step rate. The mean ± SD for sprint velocity of the 28 males in Part I was 8.29 ± 0.34 m·s^{-1},

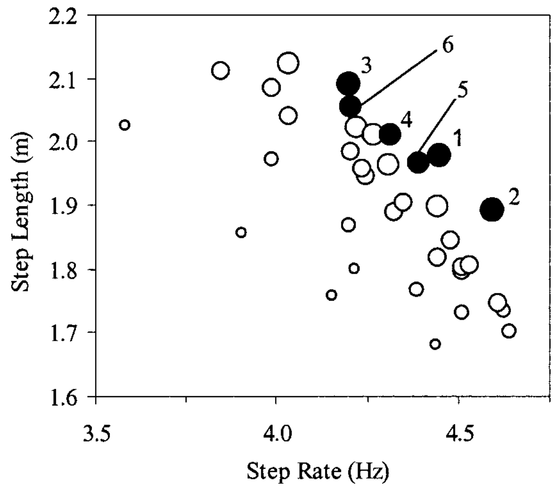

FIGURE 3—Bubble plot of the relationship among step rate, step length, and sprint velocity (indicated by the size of the bubbles). The *black bubbles* indicate the six fastest athletes, numbered from 1–6, with 1 being the fastest.

and the range was from 7.44 to 8.80 m·s^{-1}. Figure 4 shows that, as a group, step length was significantly related to sprint velocity, but step rate was not. Figure 4 also shows evidence of a strong negative interaction between step length and step rate. That is, those athletes who had a high step rate tended to have a shorter step length and *vice versa*. Flight time and flight distance were strongly related to step rate and step length, respectively; however, stance time and stance distance were not. Leg length was not significantly related to either step rate (r = −0.20) or step length (r = 0.33).

The relationships between sprint velocity and step length and step rate were also analyzed on a within-subject basis (i.e., paired *t*-tests). For the 28 male athletes, group mean ± SD for sprint velocity, step length, and step rate for the fastest trial of each athlete were 8.33 ± 0.35 m·s^{-1}, 1.92 m ± 0.13, and 4.36 ± 0.20 Hz, and for the third fastest trial of each athlete were 8.25 ± 0.33 m·s^{-1}, 1.92 ± 0.12 m and 4.31 ± 0.21 Hz. Paired *t*-tests revealed no significant difference in step length ($P = 0.97$), but step rate was significantly greater ($P < 0.05$) for the fastest trial. The average difference in sprint velocity between the fastest and third fastest trial was small (mean ± SD = 1.0 ± 0.8%); however, for 19 of the 28 athletes, the fastest trial occurred earlier in the testing session than the third fastest trial.

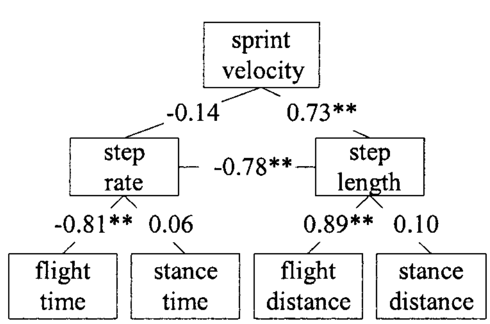

FIGURE 4—Pearson correlations for determinants of sprint velocity for 28 male athletes; *$P < 0.05$, **$P < 0.01$.

Table 2 shows the results of the multiple linear regression analyses to predict stance time, stance distance, flight time, and flight distance. Explanation of the regression output parameters is provided in the footnote of the Table. The following four paragraphs interpret the results of Table 2.

In the regression to predict stance time, the predictor variables were: mean horizontal velocity of the COM during stance, leg angle at touchdown, leg angle at takeoff, and leg length. These variables accounted for 88% ($P < 0.01$) of the variance in stance time. Some of the predictor variables were moderately interrelated; this made interpretation of the relative influence of the predictor variables, via β values, difficult. Nonetheless, it was clear that all predictor variables were significantly related to stance time. The results showed that faster sprinters had shorter stance times. Furthermore, stance time tended to be shorter when the foot landed farther under the COM at touchdown (i.e., a greater leg angle at touchdown) and when contact with the ground was terminated before the COM had traveled far beyond the stance foot (i.e., a greater leg angle at takeoff). According to the Pearson correlation coefficients, leg length was unrelated to stance time. However, when the leg angles at touchdown and takeoff, and horizontal velocity of the COM during stance were included in the multiple regression, the influence of leg length was significant.

In the regression to predict stance distance, the predictor variables were: leg angle at touchdown, leg angle at takeoff, and leg length. These variables accounted for 81% ($P < 0.01$) of the variance in stance distance. The Pearson correlations among the predictor variables were low; therefore, the β values could be used to estimate the relative influence of the predictor variables on stance distance. The results showed that stance distance was influenced most, and tended to be longer, when contact with the ground was terminated after the COM had traveled well beyond the stance foot (i.e., a smaller leg angle at takeoff). Leg length was the second most influential and was positively related to stance distance (note, again, simple correlation "missed" this relationship). Finally, stance distance was influenced least and tended to be longer when the foot landed farther in front of the COM at touchdown (i.e., a smaller leg angle at touchdown).

In the regression to predict flight time, the predictor variables were: height of takeoff and vertical velocity of takeoff. These variables accounted for 85% ($P < 0.01$) of the variance in flight time. The Pearson correlation between the two predictor variables was low; therefore, the β values could be used as estimates of the relative influence of the predictor variables on flight time. The results showed that flight time was influenced most by the vertical velocity of takeoff, then by height of takeoff (note, yet again, simple correlation "missed" this latter relationship).

In the regression to predict flight distance, the predictor variables were: height of takeoff, vertical velocity of takeoff, and horizontal velocity of takeoff. These variables accounted for 88% ($P < 0.01$) of the variance in flight distance. The correlation between the predictor variables was low; therefore, the β values could be used as estimates of the relative influence of the predictor variables on flight distance. The results showed that flight distance was influenced most by the vertical velocity of takeoff, then by height of takeoff, and then by horizontal velocity of takeoff.

Part II: the sources of the negative interaction between step length and step rate. For the 16 subjects in this analysis, there was evidence of a significant negative interaction between step length and step rate ($r = -0.70$, $P < 0.01$). That is, those subjects who had a high step rate tended to have a low step length and *vice versa*.

Table 3 shows that the long step length and high step rate groups did not significantly differ for body height, leg length, body mass, and sprint velocity. The long step length group, however, produced a longer step length by means of a longer flight distance. This was achieved by a longer flight time, caused by a greater vertical velocity of takeoff, in turn, caused by a greater vertical ground reaction impulse (GRI). Note, that there were no significant differences in horizontal velocity or height of takeoff between the two groups. Although the greater vertical velocity of takeoff used by the long step length group had a positive effect on flight time, and in turn, step length, it also had a negative effect on step rate. In brief, vertical velocity of takeoff was the kinematic source of negative interaction between step length and step rate.

Part III: the effects of manipulation of the negative interaction. The following mean data of the 28 male athletes in Part I were used as input into the simulation: stance distance, 0.96 m; stance time, 0.119 s; horizontal velocity of takeoff, 8.40 $m \cdot s^{-1}$; vertical velocity of takeoff, 0.48 $m \cdot s^{-1}$; and height of takeoff, 0.015 m. The mean values of step length, step rate, and sprint velocity (which we were trying to predict) were 1.92 m, 4.33 Hz, and 8.29 $m \cdot s^{-1}$, respectively. The regression-equation method predicted a step length, step rate, and sprint velocity of 1.91 m, 4.31 Hz, and 8.21 $m \cdot s^{-1}$, respectively. The projectile-equation method predicted 1.99 m, 4.13 Hz, and 8.21 $m \cdot s^{-1}$, respectively.

Figure 5 shows the predictions of the changes in step length, step rate, and sprint velocity, as a result of small changes in the flight-determining parameters. When comparing the calculated step length, step rate, and sprint velocity of the regression-equation method (black symbols) and the projectile-equation method (white symbols), the magnitudes did differ; however, the patterns of change were similar. Figure 5 shows that small changes in vertical velocity, angle, or height of takeoff all produced large negative interaction effects between step length and step rate, but sprint velocity was virtually unchanged. In contrast, a small change in horizontal velocity of takeoff did not produce a negative interaction effect between step length and step rate, but did affect sprint velocity. For example, for the regression-equation method, when vertical velocity of takeoff was increased by 0.20 $m \cdot s^{-1}$ (42%), step length increased by 0.26 m (14%), step rate decreased by 0.52 Hz (12%), but sprint velocity was virtually unchanged. In contrast, when horizontal velocity of takeoff was increased by 0.20 $m \cdot s^{-1}$ (2%), step length increased by 0.02 m (1%), step rate remained unchanged, and sprint velocity increased by 0.10 $m \cdot s^{-1}$ (1%).

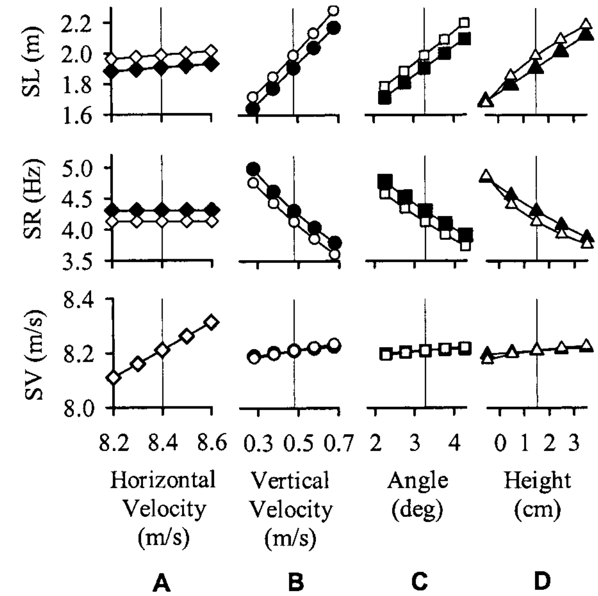

FIGURE 5—Prediction of the changes in step length (SL), step rate (SR), and sprint velocity (SV), due to changes in the flight determining parameters: A, horizontal velocity of takeoff; B, vertical velocity of takeoff; C, angle of takeoff; and D, height of takeoff. The *black symbols* are the predicted effects when using "regression equations" to calculate flight time and distance. The *white symbols* are the predicted effects when using "projectile equations" to calculate flight time and distance. The original values for horizontal velocity (8.40 $m \cdot s^{-1}$), vertical velocity (0.48 $m \cdot s^{-1}$), angle (3.3°), and height of takeoff (1.5 cm) are each indicated with a *vertical line*.

DISCUSSION

The literature contains differing opinions with regards to the relative importance of developing a long step length and high step rate in sprint running. It is clear, however, that for sprint velocity to increase, step length, step rate, or both must increase. When training an athlete to increase step length or step rate, care must be taken that the increase in one factor is not "canceled out" by a similar or greater decrease in the other factor. Subsequently, knowledge of the determinants of step length and step rate, and in particular, how step length and step rate can negatively affect one another is very important to sprint-running coaches.

For the entire group of athletes tested, and even for subgroups of athletes with similar sprint velocities, a relatively wide range of step length and step rate combinations was evident. In Part I it was found that, as a group, step length was related to sprint velocity but step rate was not. In contrast, on an individual basis, the athletes tended to produce their fastest trial (when compared to their third fastest trial) with a higher step rate, not a longer step length. This trend is in agreement with research showing that as running speed increases from almost maximum to maximum, step rate increases, whereas step length remains the same or decreases slightly (8,15). Also, Hoffman (10) noted that throughout an entire season, athletes tend to achieve their best performances with a higher step rate. He stated that "While stride length remains identical with the same sprinters in the course of the same year, the greatest stride frequency is reached in competition in the course of which the sprinter has gained his best time." However, in our case, the higher step rates recorded in the fastest trial may have been caused by optimization of technique in the fastest trial, or fatigue in the third fastest trial, or a combination of both. Nonetheless, one possible interpretation of our contrasting results from the group- and individual-based analyses is that achievement of a greater sprint velocity via a longer step length, requires long term development of strength and power (e.g., years of concentrated training to increasing horizontal GRI), whereas step rate may be the more decisive factor in the short term. This hypothesis is supported to some extent by the research of others, as presented above, but certainly requires further examination.

Part I also investigated, via multiple linear regression, the relative influence of the determinants of stance time, stance distance, flight time, and flight distance. The regression analyses to predict stance time and distance will be discussed first. Leg length and the body's position at touchdown and takeoff (as defined by the leg angle at touchdown and takeoff) were all significant in predicting stance distance. Likewise, the same predictors, but with the addition of horizontal velocity of COM during stance, were all significant in predicting stance time. The results indicated that the greater the horizontal velocity of the athlete, the shorter the time available to make contact with the ground. Certainly, an athlete must have the ability to produce high GRF in a short stance time; however, this does not necessarily mean that decreasing stance time (which deceases the time available to produce GRI) will result in the athlete running faster. The results also showed that stance time was shorter when the athlete landed with the foot farther under the COM, and when ground contact was terminated before the COM had traveled far beyond the stance foot. (Note that these techniques were also associated with a shorter stance distance). Hay (9) has suggested that these two techniques might limit horizontal braking GRF and increase step rate, respectively. However, if these techniques are to be successful in improving sprint performance, they must overcompensate for any loss in opportunity to produce a more favorable GRI. Further research is required to test these two theories.

In the regression analyses to predict flight time and flight distance, the selected predictor variables were based on the flight determining parameters of a projectile (9). However, wind resistance was not included in these regressions and probably accounts for some of the unexplained variance. The main finding of these regression analyses was that vertical velocity of takeoff accounted for a large portion of the variance in both flight time and flight distance. This does not mean, however, that vertical velocity of takeoff is more important than the other variables. Instead, we can infer from these results that, for the athletes we tested, a greater vertical velocity of takeoff had a prominent and positive effect on step length (via a greater flight distance) but also a prominent and negative effect on step rate (via a greater flight time).

Parts I and II of this study supported the existence of a negative interaction between step length and step rate. That is, the athletes who had a higher step rate tended to have a shorter step length and *vice versa*. Although our results did not support leg length as a source of this negative interaction, the results of other studies do. These studies have reported positive relationships between leg length and step length ($r = 0.60$ to 0.73), and inverse relationships between leg length and step rate ($r = -0.51$ to -0.76) (10,11,21). Step rate is likely to be lower in long-legged athletes due to the greater moment of inertia of long legs. Artificially increasing the moment of inertia of the lower limbs has been shown to have a negative effect on step rate but not step length (22). Why, though, would long-legged athletes tend to have longer step lengths? Our multiple regression results suggested two possible reasons: first, long-legged athletes tended to have longer stance distances; and second, long-legged athletes tended to have longer stance times, and therefore, a longer time to produce GRI.

Leg length may play a role in determining the combination of step length and step rate used by an athlete; however, for an individual, the effects of leg length cannot be modified, at least to any great extent. Parts II and III of this study pointed to two other (modifiable) sources of a negative interaction: vertical velocity of takeoff and height of takeoff. (Note that an increase in the angle of takeoff is very similar to an increase in vertical velocity, except that horizontal velocity is slightly decreased so that resultant velocity is held constant. Consequently, angle of takeoff will hereafter be included with any reference to vertical velocity of takeoff.) The predictions in Figure 5 showed that when either vertical velocity or height of takeoff was increased slightly, step length increased and step rate decreased, but sprint velocity was virtually unchanged. In a "true life" situation (i.e., Part II), vertical velocity of takeoff was found to be the most prominent source of the negative interaction.

How valid, though, are the predictions in Figure 5? The regression-equation method did accurately predict the measured values of step length, step rate, and sprint velocity. The projectile-equation method, however, did contain some errors (less than 5%), possibly due to ignoring wind resistance. Nonetheless, the predicted patterns of changes in step length, step rate, and sprint velocity were very similar for both methods. The main assumptions in these predictions was that the flight determining parameters could be independently altered, and that stance time and stance distance would remain constant despite these alterations. These assumptions, particularly the one for stance time, were probably only reasonable for small changes in the flight determining parameters. For example, if an athlete were to significantly increase his horizontal velocity of takeoff, and therefore his sprint velocity, it would be likely that he would also have to decrease his stance time. Therefore, the predictions in Figure 5 should be used only as a guide until further research is performed.

Vertical velocity, the prominent source of negative interaction between step length and step rate, is determined largely by vertical GRI. A previous study (26) examined vertical GRI during maximum sprint velocity (on a treadmill) and reported that faster sprinters produced the same vertical GRI as slower sprinters, but in a shorter stance time. This resulted in the faster sprinters having a longer step length (supposedly due to their greater horizontal velocity, relative to the treadmill belt). Our results suggested that a high vertical GRI (and therefore, high vertical velocity of takeoff) had a positive effect on step length; however, it also had a negative effect on step rate and basically no effect on sprint velocity. More frequent ground contacts (via a low vertical GRI and short flight time) would supposedly allow a greater opportunity for the athlete to combat the effects of wind resistance, and possibly greater opportunity to accelerate, particularly during the mid-acceleration phase of a race. Consequently, we propose it would be of advantage to direct most training effort into producing a high horizontal GRI, not vertical GRI, thereby allowing both a long step length and high step rate. This view is supported by reports that better sprinters have a lower vertical velocity of takeoff (16), and both long step lengths and high step rates (13). However, such a technique would be ineffective if the athlete did not possess the neuromuscular ability to, among other things, rapidly accelerate and decelerate the swinging lower limbs. Eccentric strength of the hamstrings (28,29) and hip flexors may play important roles here.

Past research suggests that fatigue is also likely to influence the magnitude of vertical velocity of takeoff used by a sprint athlete. Toward the end of longer sprint races (e.g., 400 m), an athlete will have a longer step length, lower step rate, increased flight time, and greater than normal vertical oscillations of COM (18,19,23). These are all signs of a greater vertical velocity at takeoff. It appears that a fatigued athlete might attempt to maintain sprint velocity, while simultaneously decreasing the energy demands of a high step rate (25), by using the negative interaction between step length and step rate to his or her advantage.

Before concluding, we must highlight two main delimitations of this study that may affect the generalizability of the results. First, the group of athletes we tested was heterogeneous with regards to sprint velocity. Such a group was selected so there would be a greater opportunity of detecting significant relationships among the variables, despite a relatively small sample size. Consequently, some of the results of this study might not necessarily apply to a more homogenous group of, say, elite track-and-field sprinters. Second, the data were collected only from the 16-m mark of the sprints. The relationships among the measured variables may be specific to this phase of a sprint. Additional research is required to see if the results of this study are applicable to other groups of athletes, and other phases of a sprint (e.g., early acceleration, maximal velocity, and deceleration phases).

In conclusion, leg length, height of takeoff, and vertical velocity of takeoff all are possible sources of a negative interaction than can occur between step length and step rate. Vertical velocity of takeoff, at least for the athletes in this study, appeared to the most prominent source. Evidence from this paper and past research suggests that the long step lengths and high step rates achieved by elite sprinters may be possible only by a technique that involves a high horizontal and low vertical velocity of takeoff. However, a greater vertical velocity of takeoff might be of advantage when an athlete is fatigued and struggling to maintain a high step rate. Finally, vertical and horizontal GRI obviously play central roles in determining vertical velocity and horizontal velocity of takeoff, respectively. Consequently, vertical and horizontal GRI are important determinants of step length and step rate. Due to their pivotal role in sprint running performance, further research is required to determine how vertical and horizontal GRI are optimized for sprint running.

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