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Relationships Between Ground Reaction Force Impulse and Kinematics of Sprint-Running Acceleration

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The literature contains some hypotheses regarding the most favorable ground reaction force (GRF) for sprint running and how it might be achieved. This study tested the relevance of these hypotheses to the acceleration phase of a sprint, using GRF impulse as the GRF variable of interest. Thirty-six athletes performed maximal-effort sprints from which video and GRF data were collected at the 16-m mark. Associations between GRF impulse (expressed relative to body mass) and various kinematic measures were explored with simple and multiple linear regressions and paired *t*-tests. The regression results showed that relative propulsive impulse accounted for 57% of variance in sprint velocity. Relative braking impulse accounted for only 7% of variance in sprint velocity. In addition, the faster athletes tended to produce only moderate magnitudes of relative vertical impulse. Paired *t*-tests revealed that lower magnitudes of relative braking impulse were associated with a smaller touchdown distance ($p < 0.01$) and a more active touchdown ($p < 0.001$). Also, greater magnitudes of relative propulsive impulse were associated with a high mean hip extension velocity of the stance limb ($p < 0.05$). In conclusion, it is likely that high magnitudes of propulsion are required to achieve high acceleration. Although there was a weak trend for faster athletes to produce lower magnitudes of braking, the possibility of braking having some advantages could not be ruled out. Further research is required to see if braking, propulsive, and vertical impulses can be modified with specific training. This will also provide insight into how a change in one GRF component might affect the others.

Key Words: braking impulse, propulsive impulse, vertical impulse

The acceleration of the center of mass of a sprinter is determined by three external forces: ground reaction force (GRF), gravitational force, and wind resis-

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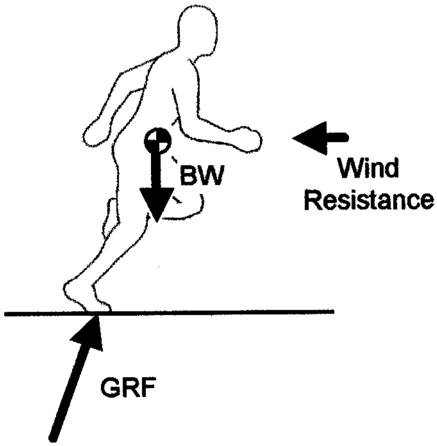

Figure 1 — The three external forces that determine the acceleration of a sprinter's center of mass: ground reaction force (GRF), gravitational force (equivalent to body weight, BW), and wind resistance.

tance (Figure 1). Of these three forces, the athlete has by far the most influence over the GRF. For analysis purposes, the GRF can be broken down into its three orthogonal components. In the case of sprint running, the horizontal (anterior-posterior) and vertical components are typically of most interest. Also of interest are the two subcomponents of the anterior-posterior horizontal GRF: a braking GRF acts posteriorly and usually occurs early in the stance phase, while a propulsive GRF acts anteriorly and usually occurs later in the stance phase.

The literature on sprint running contains a number of hypotheses regarding the various GRF components. It has been recommended that sprinters should minimize the braking GRF (Mero & Komi, 1986; Mero, Komi, & Gregor, 1992; Wood, 1987) and maximize the propulsive GRF (Mero et al., 1992). Furthermore, it has been suggested that, at maximal sprint velocity, the ability to produce a high, average vertical GRF in a short stance time is of advantage (Weyand, Sternlight, Bellizzi, & Wright, 2000).

The literature also contains hypotheses on how a sprinter can reduce the braking GRF and increase the propulsive GRF. The braking GRF is thought to be reduced by the following: using a highly active touchdown (i.e., minimizing the forward horizontal velocity of the foot, relative to the ground, immediately before ground contact) (Hay, 1994, pp. 407-408; Mann & Sprague, 1983; Wood, 1987); ensuring a high extension velocity of the hip joint and a high flexion velocity of the knee joint at the instant of touchdown (Mann, Kotmel, Herman, Johnson, & Schultz, 1984; Mann & Sprague, 1983); and minimizing touchdown distance (i.e., the distance the foot is placed in front of the center of mass at the instant of touchdown) (Mero et al., 1992). In contrast, the propulsive GRF is thought to be maximized by the following: ensuring a high angular velocity of the stance-limb hip joint (Mann & Sprague, 1983; Mann et al., 1984; Wiemann & Tidow, 1995); and fully extending the stance-limb hip, knee, and ankle joints at takeoff (see Hay, 1994, pp. 408-409 for discussion).

These hypotheses, of which many have yet to be fully tested, were probably intended to have most relevance to the maximal-velocity phase of a sprint. In contrast, we were interested in their possible relevance to the acceleration phase. Furthermore, instead of focusing on the magnitude of the GRF as such, we wanted to focus on GRF impulse. GRF impulse is an informative measure because, when expressed relative to body mass, it reflects the change in velocity of the athlete (if the effect of wind resistance is ignored).

Consequently, there were two purposes to this study. First, to determine the relationships between relative GRF impulse ("relative" indicating relative to body mass) and sprint velocity during the acceleration phase of a sprint. Second, to test the above stated hypotheses regarding the techniques to minimize braking and maximize propulsion, but from a GRF impulse perspective.

Methods

A total of 36 participants (31 M, 5 F) were tested for this study. All the men participated in sports involving sprint running (e.g., track and field, soccer, touch rugby) and all the women were track-and-field athletes. Mean ± *SD* for age, height, and body mass of the entire group were 23 ± 5 yrs, 1.76 ± 0.07 m, and 72 ± 8 kg, respectively. However, for the purpose of investigating group relationships, the entire group was considered too heterogeneous. Subsequently only the 28 fastest men (intended to represent a population of athletic men of average to very good sprint ability) were used for all regression analyses. The mean ± *SD* for age, height, and body mass of these 28 men were 22 ± 4 yrs, 1.77 ± 0.06 m, and 74 ± 6 kg, respectively. Note, though, that in other analyses in which each athlete was compared to him/herself (via paired *t*-tests), the entire group of 36 athletes was considered. Approval to undertake the study was given by The University of Auckland Human Subjects Ethics Committee. Written informed consent was obtained from each athlete.

A detailed description of the data collection and data treatment is provided elsewhere (Hunter, Marshall, & McNair, 2004). Therefore only an overview is provided here. After warming up and being prepared with joint markers, each athlete performed maximal-effort sprint-running trials, 25 m in length, on a synthetic track in which a force plate (Bertec 6090s; Bertec Corp., Columbus, OH) was embedded. The sprints were performed from a standing start, and the athletes wore spiked track shoes. *EVa 6.15* data collection system (Motion Analysis Corp., Santa Rosa, CA) was used to collect sagittal-plane video data (sampled at 240 Hz) and GRF data (sampled at 960 Hz) of a stride at the 16-m mark of the sprints. Successful trials were those in which the athlete clearly contacted the force plate without adjusting his or her natural running pattern. For this to occur, the sprint start line was adjusted by no more than 1 m. The foot to contact the force plate was the foot that was placed forward during the standing start. Typically, each athlete performed about 7 or 8 sprints which usually resulted in 4 or 5 successful trials (the range was 3 to 6 successful trials). There was a rest period of about 4 minutes between sprints.

The human body was modeled as 12 segments: feet, shanks, thighs, trunk, head (including neck), upper arms, and lower arms (including hands). Segment inertia parameters were obtained from de Leva (1996), with the exception of the foot's center of mass location which was obtained from Winter (1990). The data were filtered with a low-pass Butterworth digital filter (Winter, 1990). Kinematic

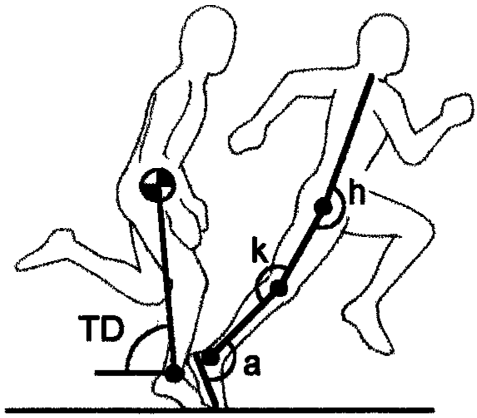

Figure 2 — Angles measured at touchdown and takeoff. The leg angle at touchdown (TD) was measured between horizontal and a line passing through the stance ankle and the body's center of mass at the moment of touchdown. Hip (h), knee (k), and ankle (a) joint angles of the stance-limb were measured at the moment of takeoff.

data were filtered with cutoff frequencies ranging from 7 Hz for upper-trunk markers to 12 Hz for foot markers. 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 the 2nd metatarsal (Hreljac & Marshall, 2000).

The following variables were calculated from the kinematic data: (a) *Sprint velocity*: mean horizontal velocity of the center of mass during the step at the 16-m mark. (b) *Hip joint kinematics*: angular velocity at the moment of touchdown, mean and maximum angular velocities during stance, and the angle at the moment of takeoff (see Figure 2). (c) *Knee joint kinematics*: angular velocity at the moment of touchdown, and angle at the moment of takeoff (Figure 2). (d) *Ankle joint kinematics*: just one measurement, the angle at the moment of takeoff (Figure 2). For this measurement the foot was represented as a link from the posterior surface of the calcaneous to the head of the 2nd metatarsal. (e) *Horizontal velocity of the foot before touchdown*: horizontal velocity, relative to the ground, of the head of the 2nd metatarsal, four frames (0.017 s) before touchdown. The lower the horizontal velocity of the foot, the more active the touchdown. That is, the athlete actively attempts to move the foot backward as fast as he or she is moving forward. (f) *Leg angle at touchdown*: measured between horizontal and a line passing through the stance ankle and center of mass, at the moment of touchdown (Figure 2). This angle was used as a measure of the horizontal distance the foot was placed in front of the center of mass at the moment of touchdown (i.e., touchdown distance).

In addition, four measures of GRF impulse (hereafter referred to as impulse) were calculated from the force-plate data: relative vertical impulse, relative horizontal impulse, relative braking impulse, and relative propulsive impulse. The term

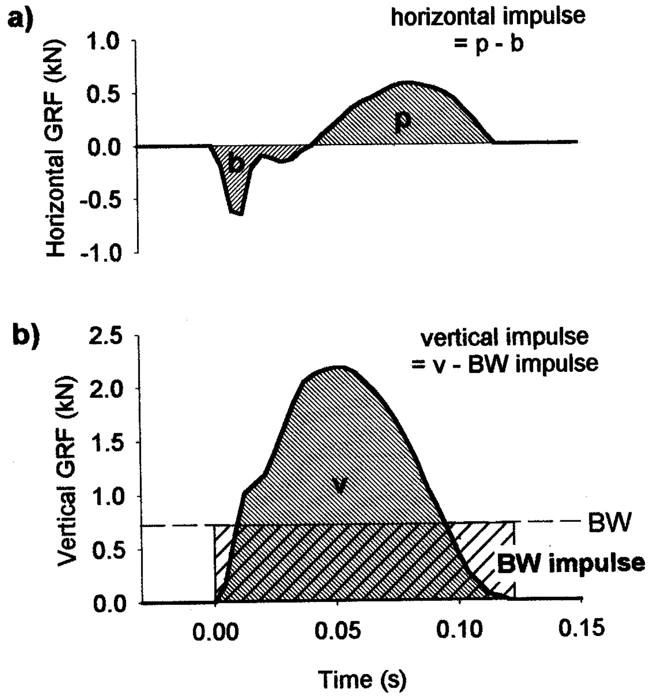

Figure 3 — Ground reaction force (GRF) impulses are shown as areas under the GRF curves. (a) p is the propulsive impulse, b is the braking impulse. Propulsive impulse was based on all horizontal positive force data during stance, and braking impulse was based on all horizontal negative force data during stance. Horizontal impulse was calculated as propulsive impulse less the absolute value of braking impulse. (b) v is the area under the vertical GRF curve, and BW impulse is the impulse due to body weight. Vertical impulse was calculated as v – BW impulse. When horizontal, braking, propulsive, and vertical impulses are expressed relative to body mass, they reflect the change in velocity of the center of mass (ignoring the effects of wind resistance) during the respective periods and in the respective directions.

"relative" has been used to indicate that the impulses were expressed relative to body mass. Relative propulsive impulse was based on all horizontal positive force data during stance, and relative braking impulse was based on all horizontal negative force data during stance. Further details of how the relative impulses were calculated are given in Figure 3.

Statistical analyses were performed in SPSS (release 10.0.5, SPSS Inc., Chicago). For all regression analyses, the means of the fastest three trials were used. For all paired *t*-tests, data from individual trials were used.

To determine the relationships between sprint velocity and the relative impulses, we performed four simple (bivariate) linear regressions with sprint velocity as the dependent variable and each relative impulse as the independent variable. From the resulting regression equations, the influence of each relative impulse on sprint velocity was assessed by calculating the predicted increase in sprint velocity associated with a one standard deviation increase in relative impulse. In addition, we performed a stepwise multiple linear regression with sprint velocity as the dependent variable and relative vertical, braking, and propulsive impulses as the independent variables. The criterion for entry into the multiple regression model was $p < 0.05$, and the criterion for removal was $p > 0.10$. Alpha was set at 0.05 for all other statistical tests.

The hypotheses regarding techniques to minimize braking (see introductory section) were assessed with paired *t*-tests. This involved selecting, from each athlete, two trials that clearly differed with regard to the magnitude of relative braking impulse, and then using paired *t*-tests on these two trials to detect differences in variables related to the braking hypotheses. That is, we wanted to know if a difference in relative braking impulse was associated with a difference in other variables of interest. For this analysis we were aware of two main requirements: (a) we needed a sample size large enough to ensured acceptable statistical power; and (b) we needed to exclude athletes for which relative braking impulse did not clearly differ (i.e., there was no point in testing for differences in the other variables if relative braking impulse itself did not differ).

These two requirements were met by using the following method. From the fastest three trials of each athlete, the trial with the greatest magnitude of relative braking impulse was named the High Braking Trial, and the trial with the lowest magnitude was named the Low Braking Trial. If the difference between these two trials was less than 0.010 m/s, then that athlete was excluded from the analysis. According to this criterion, 6 athletes were excluded, thereby leaving 28 athletes (24 M and 4 F) included in the analysis. Paired *t*-tests were then used to contrast the High vs. Low Braking Trials for the following variables: sprint velocity, relative impulses, hip and knee joint angular velocities at touchdown, horizontal velocity of the foot before touchdown, and leg angle at touchdown.

The hypotheses regarding techniques for maximizing propulsion were also assessed with paired *t*-tests. The within-subject variation of relative propulsive impulse (coefficient of variation of 4%) was smaller than that of relative braking impulse (coefficient of variation of 14%); however, the requirements of an acceptable sample size, and exclusion of athletes for which relative propulsive impulse did not clearly differ, could still be met using the following method. From all trials of each athlete (not the fastest three, as used for the braking analysis), the trial with the greatest magnitude of relative propulsive impulse was named the High Propulsion Trial, and the trial with the lowest magnitude was named the Low Propulsion Trial. If the difference between these two trials was less than 0.015 m/s, then that athlete was excluded from the analysis. According to this criterion, 6 athletes were excluded, thereby leaving 28 athletes (25 M and 3 F) in the analysis. Paired *t*-tests were then used to contrast the High vs. Low Propulsion Trials for the following variables: sprint velocity, relative impulses, mean and maximum hip joint extension velocities during stance, and hip, knee, and ankle angles at takeoff.

According to the methods of Cohen (1977), 28 athletes provided 80% power in detecting a correlation coefficient of 0.50. Also, paired *t*-tests with 28 athletes and an expected test-retest correlation of 0.80 provided more than 70% power in detecting an effect size of 0.3.

Table 1 Sprint Velocity and Relative Impulses of the 28 Male Athletes Used in All Regression Analyses

Variables	Mean	*SD*
Sprint velocity (m/s) [a]	8.29	0.34
Relative vertical impulse (m/s)	0.99	0.10
Relative horizontal impulse (m/s)	0.25	0.04
Relative braking impulse (m/s)	–0.10	0.02
Relative propulsive impulse (m/s)	0.35	0.04

[a] The range in sprint velocity was 7.44 to 8.80 m/s.

Results

Table 1 shows the means and standard deviations of sprint velocity and relative impulses of the 28 male athletes used in all regression analyses. Figure 4 shows the results of the four simple linear regression analyses. The strongest predictor of sprint velocity was relative horizontal impulse ($R^2 = 0.61$, $p < 0.001$). A one standard deviation increase (0.04 m/s) in relative horizontal impulse resulted in a predicted increase of 0.26 m/s in sprint velocity. The next strongest predictor of sprint velocity was relative propulsive impulse ($R^2 = 0.57$, $p < 0.001$). A one standard deviation increase (0.04 m/s) in relative propulsive impulse also resulted in a predicted increase of 0.26 m/s in sprint velocity (i.e., an amount identical to the previous example). The linear relationship between relative vertical impulse and sprint velocity was comparatively weak but significant ($R^2 = 0.17$, $p < 0.05$). However, this relationship showed possible departure from linearity. The 4 fastest athletes had only moderate magnitudes of relative vertical impulse (ranging from 0.96 to 1.03 m/s). Nonetheless, if using the linear regression equation, a one standard deviation increase (0.10 m/s) in relative vertical impulse resulted in a predicted increase of 0.14 m/s in sprint velocity (i.e., approx. half of the previous two examples). The simple linear regression between relative braking impulse and sprint velocity was not statistically significant ($R^2 = 0.04$, $p > 0.05$).

The multiple linear regression to predict sprint velocity resulted in relative propulsive impulse being the first variable to enter the model, and explained 57% ($R^2 = 0.57$, $p < 0.001$) of the variance in sprint velocity. Relative braking impulse was the next variable to enter the model and explained a further 7% (R^2 increase = 0.07, $p < 0.05$) of the variance. That is, the total variance in sprint velocity explained by relative propulsive impulse and relative braking impulse was 64% (total $R^2 = 0.64$, $p < 0.001$). Relative vertical impulse did not explain any further variance in sprint velocity and thus was not included in the model. The regression equation to predict sprint velocity (in m/s) was… $velocity = 7.15 \cdot p + 4.12 \cdot b + 6.18$ …where p is the relative propulsive impulse and b is the relative braking impulse, both measured in m/s. Note that relative braking impulse was quantified as a negative value to indicate its posterior direction. Therefore, the multiple linear regres-

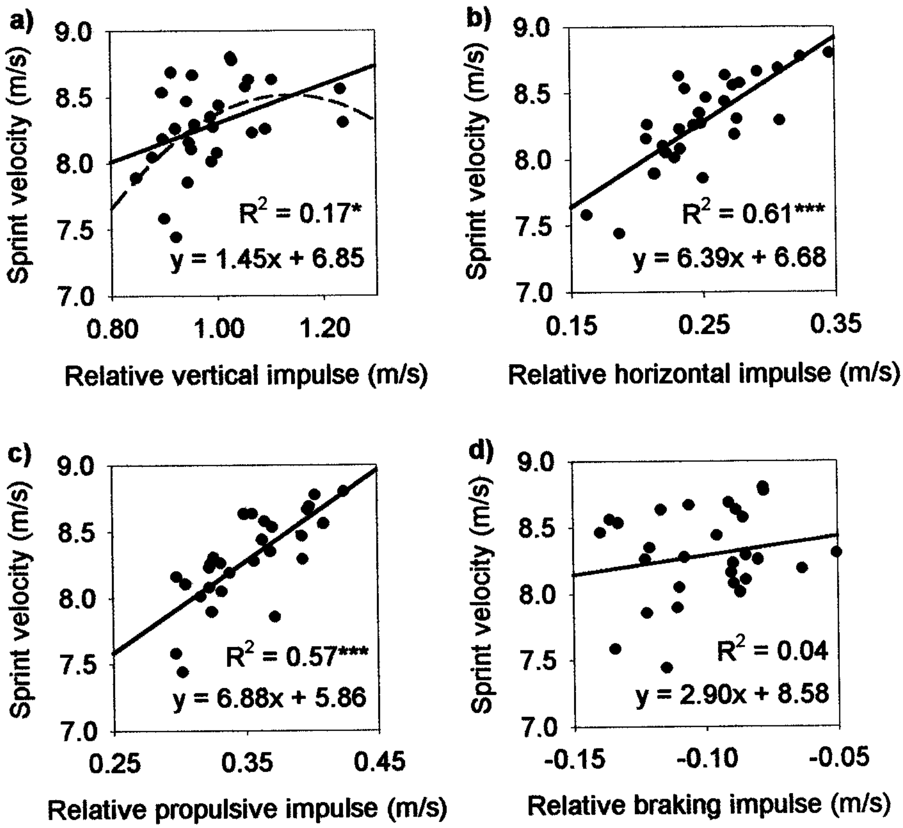

Figure 4 — Simple linear regressions between sprint velocity and relative impulses. The relationship between sprint velocity and relative vertical impulse (a) shows possible departure from linearity. A nonlinear function, such as a quadratic equation (dashed line, R^2 = 0.24), is arguably a better description of this relationship. *$p < 0.05$, ***$p < 0.001$

sion revealed that greater magnitudes of relative braking impulse had a negative effect on sprint velocity, but greater magnitudes of relative propulsive impulse had a positive effect.

Table 2 shows the results of the paired *t*-test used to analyze the hypotheses regarding techniques to minimize braking. Sprint velocity did not differ significantly, suggesting that fatigue was an unlikely cause of any of the other significant differences. The Low Braking Trials had a significantly lower relative vertical impulse, but relative propulsive impulse did not differ significantly. Of the hypotheses regarding minimization of braking, use of an active touchdown (i.e., low horizontal velocity of the foot before touchdown), and a small touchdown distance (i.e., large leg angle at touchdown) were statistically supported.

Table 3 shows the results of the paired *t*-test used to analyze the hypotheses regarding techniques for maximizing propulsion. Sprint velocity did not differ sig-

Table 2 Paired *t*-test Results for Assessment of Hypotheses Regarding Minimization of Braking

	High Braking Trials		Low Braking Trials	
	Mean	*SD*	Mean	*SD*
Sprint Velocity and Impulses				
Sprint velocity (m/s)	8.12	0.44	8.11	0.44
Relative vertical impulse (m/s)***	1.07	0.14	0.98	0.12
Relative braking impulse (m/s)*** [a]	–0.12	0.03	–0.09	0.03
Relative propulsive impulse (m/s)	0.34	0.03	0.35	0.04
Hypotheses				
Hip joint extension velocity at touchdown (deg/s)	388	93	396	75
Knee joint flexion velocity at touchdown (deg/s) [b]	–147	118	–150	88
Horizontal velocity of foot before touchdown (m/s)***	2.43	0.83	2.12	0.76
Leg angle at touchdown (deg)**	80	3	81	3

Note: [a] Negative value indicates that the impulse acted against the direction of progression of the sprinter; [b] negative value indicates flexion. 24 male and 4 female athletes were included in this analysis. **$p < 0.01$; ***$p < 0.001$

nificantly, suggesting that fatigue was an unlikely cause of any of the other significant differences. The High Propulsion Trials had a significantly lower magnitude of relative braking impulse, but relative vertical impulse did not differ significantly. Of the hypotheses regarding maximization of propulsion, a greater mean hip joint extension velocity during stance was the only hypothesis that had statistical support.

Discussion

The GRF acting on a sprinter is obviously a major determinant of sprint running performance. However, as discussed in the introductory portion, there are numerous hypotheses regarding the relative importance of the various GRF components, and how they might be altered to achieve a better sprint performance. Many of these hypotheses were probably originally intended to be most applicable to the maximal-velocity phase of a sprint. We were interested, however, in their applicability to the acceleration phase. Furthermore, we chose to focus not on the magnitude of the GRF as such, but instead on GRF impulse.

To investigate these hypotheses, we measured sprint velocity and GRF at the 16-m mark of a sprint. Sprint velocity at the 16-m mark is a product of sprint performance over that entire distance, whereas the GRF at the 16-m mark is that of a single stance phase. Nonetheless, the GRF at that mark is likely to be somewhat

Table 3 Paired *t*-test Results for Assessment of Hypotheses Regarding Maximization of Propulsion

	High Propulsion Trials		Low Propulsion Trials	
	Mean	*SD*	Mean	*SD*
Sprint Velocity and Impulses				
Sprint velocity (m/s)	8.15	0.47	8.12	0.45
Relative vertical impulse (m/s)	1.01	0.11	1.00	0.14
Relative braking impulse (m/s)* [a]	–0.10	0.03	–0.11	0.03
Relative propulsive impulse (m/s)***	0.37	0.03	0.33	0.04
Hypotheses				
Mean hip joint extension velocity during stance (deg/s)*	570	61	558	58
Max. hip joint extension velocity during stance (deg/s)	767	72	759	72
Hip joint angle at takeoff (deg)	198	4	198	5
Knee joint angle at takeoff (deg)	163	5	162	5
Ankle joint angle at takeoff (deg)	116	5	116	6

[a]Negative value indicates that the impulse acted against the sprinter's direction of progression. 25 male and 3 female athletes were included in this analysis.
*$p < 0.05$; ***$p < 0.001$

representative of an athlete's ability to apply GRF during at least some of the previous stance phases. The result of a strong relationship between relative horizontal impulse and sprint velocity supported this notion.

The first purpose of this study was to determine the relationships between the relative impulses and sprint velocity during the acceleration phase of a sprint. To examine these relationships we used both simple and multiple linear regressions. The following paragraphs contain discussion on the relationships of relative propulsive, braking, and vertical impulses with sprint velocity.

Both the simple and multiple regression results showed a relatively strong trend for faster athletes to produce greater magnitudes of relative propulsive impulse. This finding was expected because athletes with good acceleration ability would likely undergo larger increases in horizontal velocity during each stance phase. This finding is also in agreement with the research of Mero and Komi (1986), who reported a positive relationship between average resultant GRF during propulsion and sprint velocity between the 35-m and 45-m marks ($r = 0.84$, or $r = 0.65$ when the resultant GRF was expressed relative to body weight).

A simple linear regression did not support the existence of a relationship between sprint velocity and relative braking impulse. In contrast, the multiple linear regression showed a weak trend for faster athletes to produce lower magnitudes of relative braking impulse. These conflicting results, we believe, highlight a weakness in using simple linear regression alone to explore relationships among variables. In the multiple linear regression, relative propulsive impulse suppressed irrelevant variance (Tabachnick & Fidell, 2001, pp. 148-149), thereby exposing the relationship between relative braking impulse and sprint velocity. The *practical* significance of this finding, however, is arguable.

The hypothesis stating that braking should be minimized is reasonably popular with some researchers (Mero & Komi, 1986; Mero et al., 1992; Wood, 1987), and is based on the premise that a lower magnitude of braking would result in a smaller loss in horizontal velocity early in the stance phase. However, lack of evidence has led some researchers to advise caution. Putnam and Kozey (1989), for instance, warned that the braking force might be related to other important mechanical factors of performance. For example, the braking force could be involved in the storage of elastic energy (Cavagna, Komarek, & Mazzoleni, 1971). In summary, although we did find that relative braking impulse accounted for a small proportion (7%) of variance in sprint velocity, we do not know if the faster athletes actually *minimized* their magnitude of braking, and we cannot rule out that braking might also have some advantages. Further research is required to examine these issues.

The relationship between relative vertical impulse and sprint velocity showed signs of nonlinearity. The fastest athletes tended to produce only moderate magnitudes of relative vertical impulse, about 1 m/s. We speculate that, during the acceleration phase of a sprint, the most favorable magnitude of relative vertical impulse is one that creates a flight time only just long enough for repositioning of the lower limbs. If the athlete can reposition the limbs quickly, then a lower relative vertical impulse is sufficient, and all other strength reserves should be applied horizontally. However, if an athlete cannot achieve or maintain a high step rate, such as when fatigued, then a greater relative vertical impulse becomes more important.

This speculation differs somewhat from the view of Weyand et al. (2000), who proposed that a faster maximal velocity is achieved by applying a greater vertical GRF. We agree that faster sprinters have less time to apply the GRF, and therefore will require a greater force than usual. However, we believe that during the acceleration phase of a sprint, a large relative vertical impulse (i.e., notably greater than 1 m/s) will not be advantageous. Actually, a long flight time, determined by a large relative vertical impulse, may be a disadvantage. This would be due to a decrease in the percentage of time spent in contact with the ground. An athlete can only influence his or her sprint velocity when in contact with the ground. This topic remains an interesting area for future research.

The second purpose of this study was to test the hypotheses regarding the techniques for minimizing braking and maximizing propulsion. With regard to the hypotheses stating how braking can be minimized, use of a high hip extension velocity and high knee flexion velocity at touchdown were not supported. In contrast, the use of a more active touchdown (i.e., smaller horizontal velocity of the foot before touchdown) and a smaller touchdown distance (larger leg angle at touchdown) were supported. An active touchdown and small touchdown distance have long been thought to play a role in determining the magnitude of braking. For example, Hay (1994) suggested, “the horizontal velocity of the foot is the sole determinant of whether there is a braking…effect” (p. 408). In contrast, Mero et al. (1992) suggested, “The primary reason for the decrease in running velocity is the horizontal distance between the first contact point and the centre of gravity of the body at touchdown” (p. 382).

Possibly, the use of a more active touchdown is part of the cause of lower braking, and a smaller touchdown distance is a technique adjustment required to maintain balance. However, further research involving an intervention is required to test for causation. In addition, the possible effect that a decrease in braking might have on vertical impulse (see Table 2), and the consequences, should be examined.

With regard to the hypotheses stating how propulsion can be maximized, extra extension of the stance limb at takeoff was not supported. However, the use of a greater hip extension velocity was partially supported (i.e., mean, but not maximum, hip extension velocity during stance was associated with greater propulsion). The notion that the hip extensor musculature is the main determinant of thigh kinematics during stance, and therefore the main determinant of propulsion, is popular with some researchers and many coaches. For example, Wiemann and Tidow (1995) stated, “the hamstrings in particular, together with a muscle rein consisting of gluteus maximus and adductor magnus, supply the energy needed for forward propulsion, by providing a high back-swing velocity of the support leg” (p. 47). However, even if the angular velocity of the stance thigh is important in producing propulsion, we feel that further research is required to see if the hip extensor musculature is the major determinant. Putnam (1991) showed that the kinematics of the swing-limb segments in running are determined by a combination of resultant joint moments and segment interactions. It is possible that the situation is similar for the stance limb. The possible indirect contribution of the swing limb to propulsion is also largely unknown.

Before concluding, we must provide some cautionary notes regarding the results of this study. First, the results are not necessarily applicable to other phases of a sprint, for example the maximal-velocity phase. Second, we cannot predict with any confidence the relationships that might exist outside the caliber of athletes we tested. Third, we quantified *components* of the GRF. We emphasize that these components are of a single entity, the GRF, and therefore are interrelated. It is possible that a change in one component will result in a change in another component. Fourth, for all results in this paper, causation cannot automatically be assumed.

In conclusion, relative propulsive impulse accounted for 57% of the variance in sprint velocity (greater magnitudes of relative propulsive impulse were associated with faster sprint velocities). Relative braking impulse accounted for only 7% of the variance in sprint velocity (lower magnitudes of relative braking impulse were associated with faster sprint velocities). It is likely that high magnitudes of horizontal propulsion are required to achieve high acceleration. However, the practical significance of the weak relationship between braking and sprint velocity is arguable. Furthermore, the possibility that braking might have some advantages (e.g., storage of elastic energy) could not be ruled out. The faster athletes tended to produce only moderate magnitudes of relative vertical impulse. We speculated that, during the acceleration phase, the most favorable magnitude of relative vertical impulse is one that creates a flight time just long enough to allow repositioning of the lower limbs; all other strength reserves should be directed horizontally. Further research is required to see if braking, propulsive, and vertical impulses can be modified with specific training. This would provide insight into how a change in one GRF component might affect the others, and ultimately how these changes affect sprint velocity.

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