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Acceleration capability in elite sprinters and ground impulse: Push more, brake less?

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A B S T R A C T

Overground sprint studies have shown the importance of net horizontal ground reaction force impulse (IMP_H) for acceleration performance, but only investigated one or two steps over the acceleration phase, and not in elite sprinters. The main aim of this study was to distinguish between propulsive (IMP_H+) and braking (IMP_H-) components of the IMP_H and seek whether, for an expected higher IMP_H, faster elite sprinters produce greater IMP_H+, smaller IMP_H-, or both.

Nine high-level sprinters (100-m best times range: 9.95–10.60 s) performed 7 sprints (2 × 10 m, 2 × 15 m, 20 m, 30 m and 40 m) during which ground reaction force was measured by a 6.60 m force platform system. By placing the starting-blocks further from the force plates at each trial, and pooling the data, we could assess the mechanics of an entire "virtual" 40-m acceleration.

IMP_H and IMP_H+ were significantly correlated with 40-m mean speed ($r=0.868$ and 0.802, respectively; $P<0.01$), whereas vertical impulse and IMP_H- were not. Multiple regression analyses confirmed the significantly higher importance of IMP_H+ for sprint acceleration performance. Similar results were obtained when considering these mechanical data averaged over the first half of the sprint, but not over the second half. In conclusion, faster sprinters were those who produced the highest amounts of horizontal net impulse per unit body mass, and those who "pushed more" (higher IMP_H+), but not necessarily those who also "braked less" (lower IMP_H-) in the horizontal direction.

1. Introduction

Accelerating ones own body mass is a key determinant of performance in many sports such as soccer or rugby, but first and foremost in the sprint events. In the 100-m dash, the full acceleration phase (i.e. from the start to the maximal running velocity reached after about 40–70 m) has been shown to be directly related to performance (Delecluse, 1997; Delecluse et al., 1995; Mero, 1988; Mero et al., 1992). Basic laws of dynamics and experimental data explain that acceleration in the forward direction is related to the amount of net horizontal force and impulse produced and applied onto the ground, which will be returned through the ground reaction force (GRF) impulse, thereafter referred to as impulse (Hunter et al., 2005; Kawamori et al., 2012; Mero, 1988).

In the sagittal plane of motion, vertical (F_V) and horizontal (F_H) components of the resultant GRF, and the corresponding impulses (IMP_V and IMP_H, respectively) are the main determinants of the running motion and center of mass displacement. However, although F_V production has been related to the ability to achieve high maximal running speeds in humans (Weyand et al., 2010, 2000), F_H and the associated forward orientation of resultant GRF vector have recently been clearly put forward as a major determinant of acceleration and 100-m performance (Kugler and Janshen, 2010; Morin et al., 2011; Rabita et al. in press). Furthermore, previously mentioned studies found that vertical impulse was either very poorly (Hunter et al., 2005) or not significantly correlated (Kawamori et al., 2012) with acceleration performance.

Since a typical running support phase may be divided into a braking phase (backward orientation of the F_H vector; braking

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impulse $IMP_{H}-$) and a propulsive phase (forward orientation of the F_{H} vector; propulsive impulse $IMP_{H}+$), the net horizontal impulse IMP_{H} is the sum of $IMP_{H}-$ and $IMP_{H}+$. Consequently, a given amount of IMP_{H} could result from many combinations of $IMP_{H}-$ and $IMP_{H}+$ values. Therefore, in practical terms, to accelerate well (i.e. produce a high IMP_{H}), a sprinter could push more (i.e. increase $IMP_{H}+$) and/or brake less (i.e. decrease $IMP_{H}-$), and the sprint training process could be related to these possibilities. In addition, previous studies on accelerated walking in humans (Orendurff et al., 2008; Peterson et al., 2011) and accelerated locomotion in animals (McGowan et al., 2005; Roberts and Scales, 2002; Walter and Carrier, 2009) have shown that forward acceleration of the body could be achieved by modulating $IMP_{H}-$ and $IMP_{H}+$, provided that IMP_{H} increased.

In the area of sprint running performance, it is interesting to note that few studies have specifically addressed the issue of the relative importance of IMP_{H} and its braking and propulsive components for acceleration performance. Hunter et al. (2005) measured GRF impulses for one single step at the 16-m mark of a typical 25-m sprint in 36 non-specialist athletes. These authors showed that relative (i.e. normalized to body mass) IMP_{H} and $IMP_{H}+$ were the strongest predictors of sprint velocity. Using simple linear regression, $IMP_{H}-$ was not related to sprint velocity ($r^2=0.04$). When entering both $IMP_{H}-$ and $IMP_{H}+$ in a multiple regression model, these two variables explained significant parts of the variance in running velocity: 7% and 57%, respectively. These authors highlighted the importance of the multiple regression approach to test the relationship between acceleration performance and both $IMP_{H}-$ and $IMP_{H}+$, independently from one another. Furthermore, they commented on the fact that although relative $IMP_{H}-$ accounted for a small proportion (7%) of the variance in sprint velocity, further studies were needed to find out whether "*faster athletes actually minimized their magnitude of braking*". Using a very similar protocol (30 team sport players performed 10-m sprints, and impulses were computed from GRF recorded over one single step for the first contact, and the contact at 8 m after the start), Kawamori et al. (2012) showed that relative IMP_{H} and $IMP_{H}+$ measured at 8 m were significantly correlated with 10-m time, but relative IMP_{V} and $IMP_{H}-$ were not. The authors therefore discussed the "*lack of evidence that smaller braking impulse was associated with better sprint acceleration performance*". Finally, Mero (1988) studied the first contact following the starting-blocks push-off in 4 sprinters and showed that IMP_{V} was not significantly correlated to running velocity, whereas $IMP_{H}+$ was. However, they did not detail the correlations with IMP_{H} and $IMP_{H}-$.

The main limitation of these studies is that impulses were only measured for one to five steps over an entire acceleration, and/or included non-specialist sprinters of heterogeneous levels of performance, and/or data of $IMP_{H}+$ and $IMP_{H}-$ were not analyzed using a multiple regression model. This statistical approach makes possible to investigate the complementary effects of several independent variables together. In the present study, we had the unique opportunity to measure GRF impulses for almost all steps of 40-m sprints in elite and sub-elite sprinters, and thus to experimentally address the question of whether elite sprint acceleration performance depends on "pushing more" and/or on "braking less" in the horizontal direction.

The first aim of this study was to investigate the relationships between GRF impulses produced over a 40-m sprint and overall acceleration performance in elite sprinters. Our hypothesis was that relative IMP_{V} would not be significantly correlated with performance, but relative IMP_{H} would. The second aim was to investigate the independent relative importance of horizontal braking and propulsive impulses.

2. Methods

2.1. Subjects and experimental protocol

Nine male elite (international level) or sub-elite (French national level) sprinters (mean ± SD: age = 23.9 ± 3.4 years; body mass = 76.4 ± 7.1 kg; height = 1.82 ± 0.07 m) gave their written informed consent to participate in this study, conducted according to the declaration of Helsinki II, and approved by the local ethical committee. Their personal 100-m best times at the moment of the study were 10.37 ± 0.27 s (range: 9.95–10.60 s).

The sprinters were tested on the indoor track of the French Institute of Sport (INSEP) during a standard sprint training session. After a 45 min warm-up managed by their personal coach, the athletes performed 7 sprints: 2 × 10 m, 2 × 15 m, 20 m, 30 m and 40 m with 4 min rest between each trial. During these sprints, vertical, horizontal and mediolateral components of the GRF were measured by a 6.60 m force platform system (natural frequency ≥ 500 Hz). This system consisted of 6 individual force plates (1.2 × 0.6 m, 5 length-wise and 1 sideways) connected in series, and covered with a tartan mat leveled with the stadium track and invisible to the runners while sprinting. Each force plate was equipped with piezoelectric sensors (KI 9067; Kistler, Winterthur, Switzerland). Instantaneous GRF signals were digitized at a sampling rate of 1000 Hz.

The protocol was designed in order to virtually aggregate the characteristics of a single complete 40-m sprint for each athlete. To do so, the starting blocks, initially placed over the first platform for the 10 m sprints were progressively placed further from the force plates for the subsequent trials (15–40 m) so that in total 17 different steps (18 foot contacts) from the block to the 40 m line could be measured. Indeed, the measurement zone allowed GRF recordings of 5 successive foot contacts for the 10 m trials (including the blocks pushing phase), 4 contacts for the 15 m trials, and 3 contacts for the 3 other trials (20, 30 and 40 m). Before pooling the data, we checked the repeatability of performance and kinematic data measured over the starting phase of the seven sprints. Indeed, after approximately 8 m of sprinting (i.e. at the 6th step) a strong repeatability was reported for several variables such as performance, step length or contact times. Therefore, all bouts were performed with the same maximal involvement of the subjects in the starting phase of the run (whatever the total distance to achieve) confirming all data could be pooled to study the mechanics of a "virtual" 40-m acceleration. For full details on this experimental design and its validity, see Rabita et al. (in press).

2.2. Mechanical variables

Force platform signals were low-passed filtered (200 Hz cutoff, 3rd order zero-phase Butterworth). Then, instantaneous data of vertical and horizontal GRF (see Fig. 1 in Rabita et al., in press) were averaged for each contact phase (10 N threshold), and expressed in both N and N\kg of body mass (N kg^{-1}). In the sagittal plane of motion, horizontal and vertical GRF impulses were computed for each support phase by integrating the values of GRF over each contact time as follows (note that IMP_{V} was computed by subtracting the impulse due to body weight):

$$IMP_{V}= \int_0^t (F_V - m.g)\mathrm{d}t \tag{1}$$

$$IMP_{H} = \int_0^t F_H \,\mathrm{d}t \tag{2}$$

In addition, distinction was made between the horizontal braking ($IMP_{H}-$) and propulsive ($IMP_{H}+$) impulses, defined by negative and positive values of F_H, respectively, and integrated over the corresponding periods. Data were then averaged through three phases: starting-block push-off, entire 40-m sprint, first half of the acceleration (0–20 m section, starting-block push included) and second half of the acceleration (20–40 m section). This 20-m split was chosen in accordance with the "breakpoint" phenomenon presented in detail by Nagahara et al. (2014), who showed that a breakpoint in sprint acceleration kinematics occurred around the 20-m mark.

Impulse data were expressed in N s, and then normalized to body mass (thus expressed in m s^{-1}), in order to reflect the changes in velocity of the subjects' center of mass (Hunter et al., 2005; Kawamori et al., 2012).

2.3. Performance variables

Standard photoelectric cells (Brower timing system, Draper, USA) were used to measure 40-m sprint times, and compute 40-m mean velocity (V_{40}, expressed in m s^{-1}). The photocells chronometer was triggered by the loss of contact between subjects' hand and the pressure sensor placed on the ground at the starting line.

2.4. Data analysis and statistics

Descriptive statistics are presented as mean values ± SD. Normal distribution of the data was checked by the Shapiro–Wilk normality test. Pearson's correlations were used to test the relationship between mechanical variables and performance. The specific analysis of the independent effects of IMP_H+ and IMP_H- on acceleration performance was performed using a multiple regression model with 40-m performance (V_{40}) as the dependent variable, and IMP_H+ and IMP_H- as independent variables. In order to reflect the braking feature of IMP_H- and for more clarity in the interpretation of the results, absolute values of IMP_H- were used in the multiple regressions. All impulse values were averaged values for all steps over the entire 40-m or the 0–20 m and 20–40 m sections. The significance level was set at $P<0.05$.

3. Results

40-m times were 5.10 ± 0.24 s (ranging from 4.81 to 5.58 s). This corresponded to V_{40} of 7.86 ± 0.36 m s^{-1} (ranging from 7.17 to 8.32 m s^{-1}). Table1 shows the main mechanical variables, and Fig. 1 shows the values of IMP_H, IMP_H- and IMP_H+ for all the running steps analyzed over the 40-m.

Fig. 1 shows that step after step during the sprint acceleration, IMP_H decreased first due to the decrease in IMP_H+ (first 6–7 steps), and then due to the higher IMP_H-. This detailed analysis of IMP_H+ is further shown in the comparison of instantaneous horizontal GRF over time for the fastest and the slowest individuals of the group (Fig. 2).

When considering mechanical data averaged over the entire 40-m, simple correlation analyses showed that V_{40} was not significantly correlated with IMP_V ($r=-0.503$; $P=0.09$). Contrastingly, IMP_H was significantly correlated with V_{40} ($r=0.868$; $P<0.01$). IMP_H+ was significantly correlated with V_{40} ($r=0.802$; $P<0.01$) whereas IMP_H- was not ($r=-0.295$; $P=0.441$). These correlations are shown in Fig. 3.

Finally, IMP_H+ and IMP_H- were not correlated ($P=0.770$), and the multiple regression analysis showed that when IMP_H+ and IMP_H- were taken together as independent variables, only IMP_H+ explained a significant part of V_{40} (partial $P<0.01$, Table 2), whereas only a non-significant tendency was observed for IMP_H- (partial $P=0.08$, Table 2).

When considering the mechanical data averaged over the 0–20 m section of the sprint only, similar results were observed for the simple correlation analysis: V_{40} was not significantly correlated with IMP_V ($r=-0.579$; $P=0.102$), but was with IMP_H ($r=0.877$; $P<0.01$). IMP_H+ was significantly correlated with V_{40} ($r=0.833$; $P<0.01$) whereas IMP_H- was not ($P=0.539$), and the multiple regression analysis showed again that only IMP_H+ explained a significant part of V_{40} (partial $P<0.01$, Table 3).

Last, when considering the mechanical data averaged over the 20–40 m section, none of the simple correlations tested between mechanical variables and V_{40} was significant (highest correlation for IMP_H with $r=0.568$; $P=0.111$).

4. Discussion

The main results of this study of high-level sprinters were that:

(1) In accordance with our hypothesis, relative vertical GRF impulse averaged over the entire 40-m was not correlated to sprint acceleration performance, whereas relative horizontal net impulse was;
(2) Within this horizontal net impulse, propulsive impulse explained an important part (about 75%) of the performance variability between athletes (i.e. faster sprinters were those who showed the highest values of propulsive impulse), whereas no significant correlation was observed for braking horizontal impulse;
(3) No significant correlation between any kind of GRF impulse and 40-m performance was observed when considering 20–40 m values.

When compared with similar units and computations (e.g. taking into account or not the vertical body weight impulse), the present values of GRF impulses are in the line with or higher than those previously reported, at similar distances along the 40-m sprint. Mero (1988) reported IMP_H average values of 223 N s in the starting-blocks pushing phase versus 268 N s in the present study. Kawamori et al. (2012) and Hunter et al. (2005) reported relative IMP_H average values of 0.37 m s^{-1} and 0.25 m s^{-1} at the 8-m and 16-m marks of a standing start sprint respectively, versus averaged values of 0.56 m s^{-1} and 0.36 m s^{-1} for the corresponding steps of this study. The substantially higher values we observed are consistent with the clearly higher level of the athletes tested in the present study compared to the three other protocols cited: 100-m best times ranging from 9.95 to 10.60 s here versus 10.45 to 11.07 s for Mero (1988), and populations of physically active sportsmen who were not sprinting specialists (Kawamori et al., 2012) and/or not high-level sprinters (Hunter et al., 2005). Finally, our values of IMP_V and IMP_H in the blocks phase correspond to changes in center of mass velocity that are close to those reported by Slawinski et al. (2010) in a similar elite group for the block pushing phase. Another

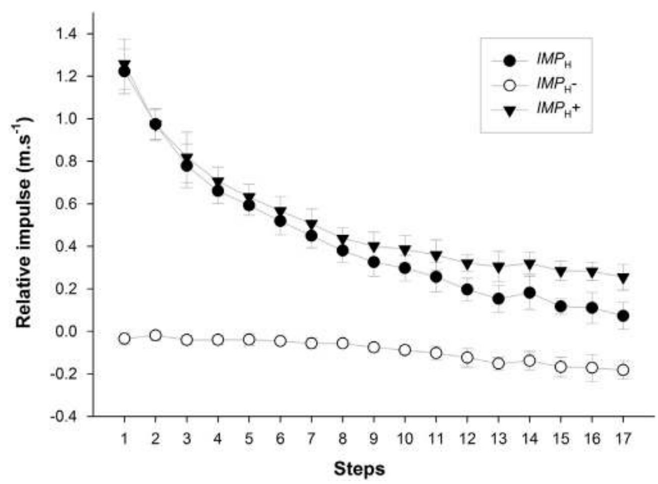

Fig. 1. – Net (filled circles), propulsive (triangles) and braking (empty circles) relative impulses for the 17 steps analyzed over the 40-m sprints. Starting-blocks push-off data are not presented.

Table 1
Mean(SD) values of mechanical variables for the starting-blocks push-off, and averaged over the entire 40-m sprint, and the 0–20 m and 20–40 m phases.

Variable	Starting-blocks		0–20 m phase		20–40 m phase		Entire 40-m	
Absolute IMP_V (N s)	51.9	(9.66)	63.5	(8.61)	89.0	(10.0)	72.1	(8.47)
AbsoluteIMP_H (N s)	268	(35)	64.1	(9.03)	10.6	(2.9)	46.0	(6.5)
Absolute IMP_H- (N s)	0.00	(0.00)	−3.79	(1.27)	−11.7	(1.7)	−6.45	(1.31)
Absolute IMP_H+ (N s)	268	(35)	67.8	(9.6)	22.2	(3.8)	52.3	(7.2)
Relative IMP_V (m s^{-1})	0.652	(0.086)	0.798	(0.057)	1.12	(0.09)	0.906	(0.050)
Relative IMP_H (m s^{-1})	3.37	(0.27)	0.805	(0.061)	0.132	(0.030)	0.577	(0.044)
Relative IMP_H- (m s^{-1})	0.00	(0.00)	−0.047	(0.013)	−0.147	(0.016)	−0.081	(0.011)
Relative IMP_H+ (m s^{-1})	3.37	(0.27)	0.851	(0.060)	0.279	(0.029)	0.657	(0.044)

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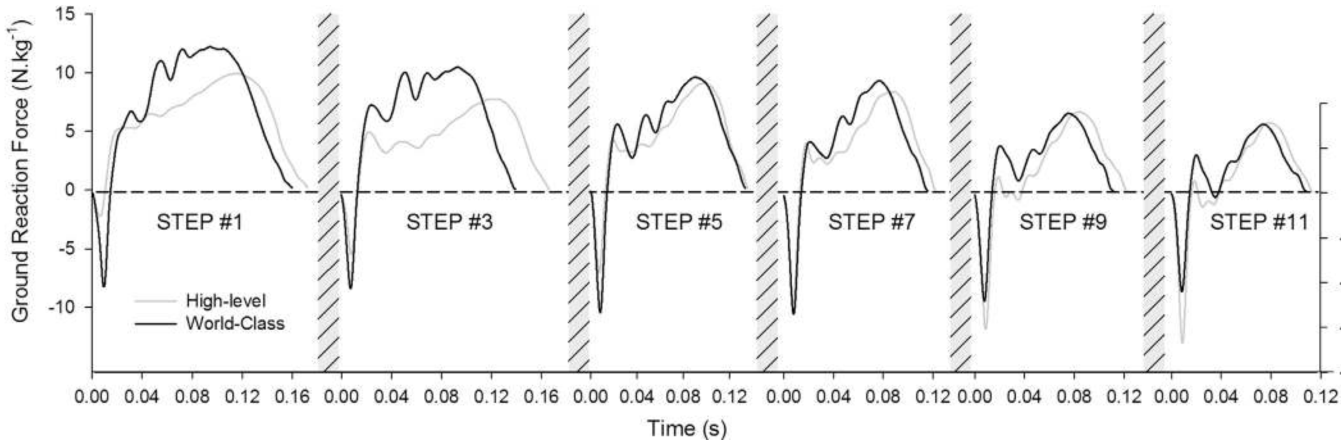

Fig. 2. – Comparison of instantaneous horizontal ground reaction force during the support phases of the 1st, 3rd, 5th, 7th, 9th and 11th steps of a 40-m sprint between a world-class sprinter (100-m best time of 9.95 s, black lines) and a high-level sprinter (100-m best time of 10.60 s, grey lines). Only odd-numbered steps are shown for clarity reasons.

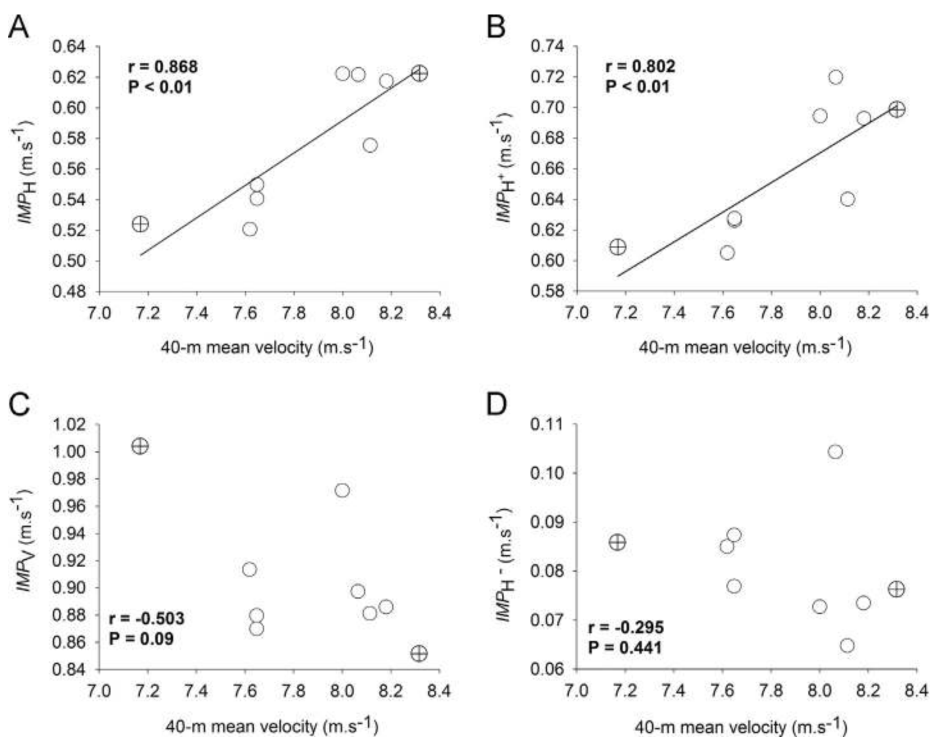

Fig. 3. – Correlation between 40-m performance (mean running velocity) and relative net horizontal (panel A.), propulsive (panel B.), vertical (panel C.) and braking (panel D.) impulses. Crossed dots indicate the two typical subjects compared in Fig. 2 (fastest and slowest subjects of the group).

important difference between the present and previous studies is that almost all steps of "virtual" 40-m sprints (Fig. 1) could be measured and average values could be presented that are more representative of the entire sprint acceleration than punctual values of only one step at a given point of the sprint.

Our results confirm that 40-m sprint performance is significantly related to high values of IMP_H ($r=0.868$; $P<0.01$). Furthermore, using both simple correlations and multiple regression analysis, as in previous studies, we showed that within this IMP_H production, performance was significantly and positively correlated to IMP_H+ (Table 2; partial $P<0.01$), confirming that in addition to net horizontal impulse, propulsive horizontal impulse is a key factor of sprint performance (Hunter et al., 2005; Kawamori et al., 2012). Faster athletes were those who "pushed" the most in the horizontal direction. The other main finding brought by the present study is that faster athletes were not necessarily those who "braked" the least: we found that IMP_H- was not correlated to performance ($P=0.441$), and only a non-significant tendency was found (Table 2, partial $P=0.08$) with the multiple regression model used, making

Table 2
Multiple regression analysis for the prediction of sprint acceleration performance (V_{40}). Values of mechanical variables are averaged over the entire 40-m.

Multiple regression model	r^2	SEE (m s^{-1})	*P*
	0.795	0.191	0.009
Independent variables	**Coefficient**	***t***	***P***
IMP_H+	7.01	4.55	0.004
IMP_H-	−12.4	−2.10	0.08
Constant	4.26	3.98	0.007

SEE: Standard error of estimate.
IMP_H+: Relative propulsive impulse (m s^{-1}).
IMP_H-: Relative braking impulse in absolute value (m s^{-1}).

Table 3
Multiple regression analysis for the prediction of sprint acceleration performance (V_{40}). Values of mechanical variables are averaged over the 0–20 m part only.

Multiple regression model	r^2	SEE (m s^{-1})	P
	0.805	0.186	0.007
Independent variables	**Coefficient**	***t***	***P***
IMP_H+	5.26	4.80	0.003
IMP_H-	−9.63	−1.84	0.115
Constant	3.84	4.10	0.006

SEE: Standard error of estimate.
IMP_H+: Relative propulsive impulse (m s^{-1}).
IMP_H-: Relative braking impulse in absolute value (m s^{-1}).

the importance of IMP_H- less clear than IMP_H+. These two results show that acceleration in sprint running is clearly related to the ability to produce a high amount of IMP_H mainly through a high IMP_H+. Fig. 1 shows that step after step during the sprint acceleration, IMP_H decreased mainly due to the decrease in IMP_H+ during the first phase of the acceleration (first 6–7 steps). In a second phase, IMP_H decreased mainly because of the higher IMP_H-. Fig. 2 shows these changes in both phases. In the first phase the main difference in the horizontal GRF pattern between faster and slower sprinters is in the positive GRF values rather than the negative ones (first 6–7 steps) and in the second phase the main difference is in the negative GRF values rather than the positive ones (9–11 steps).

Interestingly, literature on accelerated locomotion in animals has shown that wallabies accelerate by modulating their braking and propulsive horizontal ground reaction forces with rather constant vertical ground reaction force (McGowan et al., 2005), and that wild turkeys accelerate by "*both decreasing the braking component of the horizontal ground reaction force and increasing the propulsive force*" (Roberts and Scales, 2002). Contrastingly, it seems that specialized humans mainly modulate their propulsive impulse, at least for the sub-elite and elite athletes group tested in this study. It is possible that less skilled humans show a much greater IMP_H- than sprint specialists, but the main focus of this study was to specifically discuss the relative importance of braking and propulsive impulses in high-level individuals and how this related to their sprint acceleration performance. Note that although this population might seem homogeneous, the range of performances (from 9.95 to 10.60 s) is not that narrow, and the fact that significant and high correlations were obtained in this specific group highlights the high importance of propulsive ground impulse for sprint acceleration performance.

Two other important results have been obtained. First, IMP_V was not correlated to sprint acceleration performance. Fig. 3 shows that in this group of high-level sprinters, there is even a non-significant tendency ($P=0.09$) towards a negative correlation between IMP_V and 40-m performance. This negative trend was further supported by the results of a multiple regression analysis testing the independent influence of IMP_V and IMP_H on V_{40} (negative coefficient and partial P of 0.01 for IMP_V). This absence of correlation between vertical impulse and sprint acceleration performance is what Kawamori et al. (2012) also found, and in line with the moderate (although significant) relationship ($r=0.41$) between vertical impulse at the 16-m mark and sprint velocity found by Hunter et al. (2005). This significant importance of horizontal impulse and null (or very low) importance of vertical impulse on track acceleration and sprint performance is also well in line with the recent results of Kugler and Janshen (2010), Morin et al. (2011, 2012), Rabita et al. (in press) who showed, in subjects ranging from non-specialists to world-class individuals, that the horizontal component of the resultant GRF produced during both treadmill and overground sprints was significantly related to sprint performance, whereas the magnitude of the vertical component was not. These results are consistently showing the relatively higher importance of horizontal force production compared to vertical force production during acceleration. However, they seem contradictory with the conclusions of Weyand et al. (2000), who showed that individuals who reached the highest running speed on the track were those who produced the highest amounts of vertical GRF per unit bodyweight on an instrumented treadmill. This might be explained, in addition to the fact that Weyand et al.'s data were only focused on vertical GRF and obtained on an instrumented treadmill, by the fact that the present study, as well as Kawamori et al.'s and Hunter et al.'s considered the acceleration phase of a sprint, and not the instant of top speed only. Furthermore, we directly correlated ground impulses and performance both recorded during the same accelerations. In addition to athletics, the potential applications of these results concern several sports in which acceleration, rather than top speed, is a fundamental feature of performance (rugby, soccer, etc.). Second, it is very interesting to notice that when dividing the analysis into two 20-m sections of the acceleration, the above-discussed correlations found with mechanical values averaged for the entire 40-m are similar when averaging values over the 0–20 m steps (Table 3), but no correlation was found between 40-m performance and any of the mechanical variables when averaged over the 20–40 m section of the sprint. This suggests that much of the 40-m sprint acceleration performance is determined, from a mechanical point of view, by how much IMP_H is produced over the 20 first meters of the run, with as much IMP_H+ as possible.

The inevitable limitation of the present study is that we cumulated the data of several sprints for each individual in order to virtually "reconstruct" a complete 40-m. As discussed in details by Rabita et al. (in press), the high reproducibility of data obtained on such high-level sprinters show that the methodological approach used here to study an entire (although virtual) 40-m is reliable.

In conclusion, this study shows that faster sprinters are those who produce the highest amounts of horizontal net impulse per unit body mass, and that vertical ground reaction force impulse is not related to 40-m sprint performance. Furthermore, within this higher amount of net horizontal impulse, faster sprinters are those able to "push more" (i.e. produce higher amount of propulsive horizontal impulse), but not necessarily to "brake less" (i.e. produce lower amount of braking impulse), especially in the 0–20 m section of the sprint. Since these conclusions may find interesting applications in the field of sport training, further studies should now investigate how (sprint technique, kinematics, muscle coordination, specific training) to push more during the stance phase, an event lasting roughly 100 ms or less in top level athletes.

Conflict of interest

We declare that we have no conflict of interest.

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