FORCE PRODUCTION IN THE FIRST FOUR STEPS OF SPRINT RUNNING

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The purpose of this investigation was to understand how the athlete produces acceleration during the first steps of sprint running. One athlete performed four starts from starting blocks over a series of four force plates. Horizontal impulse (which directly relates to the acceleration of the athlete) gradually decreased after leaving the blocks, while this decrease was transferred to a gradual increase in vertical force production to support the small but required vertical movement of CM in order to increase flight time (to gain longer steps). It also seems that the body can compensate for some technical mistakes during the performance, as the results revealed that an extended braking time in one step yielded a reduced braking time in the next step. This implied that the increased time in the contact was used to get other body parts into more favourable positions for the next step.

KEY WORDS: sprint start, force plate, acceleration, kinetic, starting blocks, sprinting

INTRODUCTION: Biomechanical studies in sprinting have recently concentrated on the mid-acceleration phase (Johnson and Buckley, 2001; Hunter et al., 2005) or on the maximal velocity phase (Kuitunen et al., 2002). Johnson and Buckley (2001) studied running at about the 14-m mark and found the role of knee to be maintaining the centre of mass height and allowing power to be transferred from hip to ankle. Hunter et al. (2005) investigated the influence of different impulses on running velocity at the 16-m mark, and found that the best predictor was the relative horizontal impulse. Whilst both studies have provided important information, these papers have concentrated on a single point of the mid-acceleration phase. Start phase studies are generally from an earlier time than the aforementioned studies. These have concentrated mainly on the set position and block clearance, i.e. the first movements on and from the blocks (e.g. Henry, 1952; Guissard et al., 1992; Schot and Knutzen, 1992). As Henry (1952) stated, the vertical thrust out of the blocks might be important for good running, however, it's only the horizontal thrust which contributes to forward motion off the blocks. Mero et al. (1983) echoed this importance of horizontal impulse on the block leaving velocity. Further, Mero (1988) produced force plate information from the first step after the blocks. Horizontal force impulse of the propulsion phase during the first step (90 ± 11 Ns) correlated significantly ($r = .71$, $p < 0.05$) with the running velocity at the end of the first contact. Whilst a positive net horizontal impulse is needed to increase the running speed of the athlete, it can be concluded that this impulse will eventually decrease close to zero by the maximum velocity phase (in the maximum velocity phase the overall horizontal velocity does not change, thus only a small net horizontal impulse is required to overcome air resistance). Interestingly, Weyand et al. (2000) showed that the faster running speeds depended upon greater vertical ground reaction forces. Thus, it could be hypothesised that there must be a shift of importance from predominantly horizontal force production at the start to vertical force production in the later stage of the run. The literature, however, does not provide kinetic information beyond the first step after the blocks before the mid-acceleration phase. The acceleration though is the largest at the start and during the first steps off the blocks. Thus, the purpose of this investigation was to understand how the athlete produces this high acceleration during the first steps of sprint running.

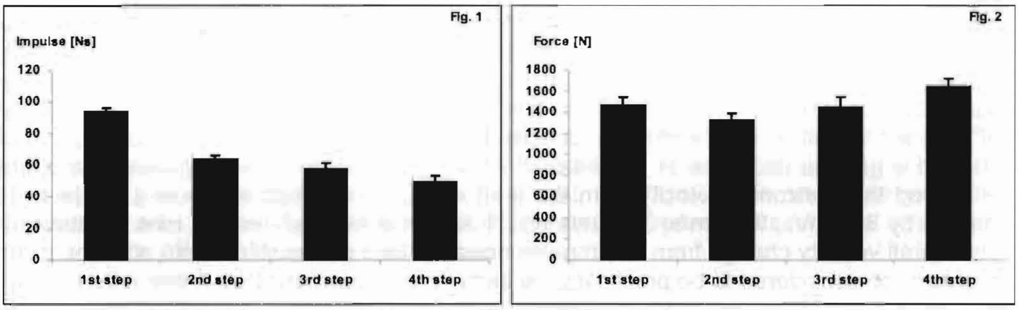
METHODS: A male athlete gave informed consent and participated in this study during the indoor competition season. The study follows a single subject analysis procedure, as in sport it is often important to be aware how an individual athlete reacts and is affected by the stimulus (Bates, 1996). Also, Dixon and Kerwin (2002) showed that a single participant's behavior could be overlooked at the group level.
The athlete's age was 28 years, height 1.78 m and mass 79.2 kg at the time of the study.

The personal best for 100 m was 10.80 s. After a normal individual warm-up, the athlete performed four successful 30 m sprint start trials with a recovery of 8 to 10 minutes between trials to avoid the effects of fatigue. The first four steps after leaving the starting blocks were run on a series of force platforms (TR-Testi, Finland). Each of the four plates were covered with a normal synthetic running track and each plate was individually calibrated. Vertical and horizontal (anterior-posterior) forces were collected at 1000 Hz. At the start of the each run, a non-loading period of data over 0.5 s was collected to set the zero level. A range of two SDs from the mean base line noise was set as a threshold to determine when the foot was or was not in contact with the track. Raw force signals were further handled with a 5-point moving average. The following kinetic and timing variables were collected from each step: Maximum vertical force during the propulsion phase ($maxF_y$), timing of this maximum F_y force from the start of the contact ($maxF_{ytime}$), maximum horizontal braking ($maxF_{x-}$) and propulsion force (max F_{x+}), timing of these maximum F_x forces ($maxF_{x\text{-}time}$ and $maxF_{x+time}$), the absolute and relative (from the whole step contact time) length of the horizontal braking ($absF_{x\text{-}time}$ and $relF_{x\text{-}time}$) and propulsion phases ($absF_{x+time}$ and $relF_{x+time}$), maximum cumulative horizontal braking impulse ($maxF_{x\text{-}imp}$), net horizontal impulse ($netF_{ximp}$), contact times (t_{cont}), and the flight times between the steps (t_{flight}). Impulse information was divided by the subject's mass to get horizontal velocity changes due to the impulses (Δv_{neg} and Δv_{pos}, respectively).

RESULTS: Net horizontal impulse was largest in the first contact after which it gradually decreased (Figure 1). The maximum vertical force in the propulsion phase yielded relatively large values in the first contact (Figure 2). There was a clear drop in this value in the second contact after which it gradually increased and gained larger values than in the first step only in the fourth step after leaving the blocks. The rest of the kinetic and timing variables are presented in Table 1.

Table 1 Kinetic and timing variables for each step after the blocks. Values are mean ± SD. (*) flight time is the time from the current step to the next step.

		1st step	2nd step	3rd step	4th step
$maxF_{ytime}$	[s]	0.120±0.012	0.099±0.015	0.084±0.010	0.058±0.006
$maxF_{x-}$	[N]	-215±116	-348±72	-421±36	-672±170
$maxF_{x\text{-}time}$	[s]	0.007±0.000	0.007±0.001	0.006±0.000	0.006±0.001
max F_{x+}	[N]	852±46	709±35	704±19	751±36
$maxF_{x+time}$	[s]	0.147±0.017	0.132±0.009	0.122±0.011	0.096±0.016
t_{cont}	[s]	0.200±0.014	0.173±0.011	0.159±0.010	0.135±0.008
$absF_{x\text{-}time}$	[s]	0.012±0.001	0.014±0.001	0.012±0.000	0.013±0.001
$relF_{x\text{-}time}$	[%]	6.3±0.6	8.2±0.3	7.7±0.4	9.9±1.5
$absF_{x+time}$	[s]	0.188±0.014	0.159±0.009	0.147±0.009	0.122±0.009
$relF_{x+time}$	[%]	93.7±0.6	91.8±0.3	92.3±0.4	90.1±1.5
t_{flight} (*)	[s]	0.045±0.010	0.058±0.005	0.074±0.003	0.081±0.005
$maxF_{x\text{-}imp}$	[Ns]	-1.5±1.0	-2.9±0.7	-2.9±0.3	-4.8±1.4
Δv_{neg}	[m/s]	-0.02±0.01	-0.04±0.01	-0.04±0.00	-0.06±0.02
Δv_{pos}	[m/s]	1.18±0.03	0.80±0.03	0.73±0.04	0.62±0.04



Figures 1 and 2 Net horizontal impulse (Figure 1), and the maximum vertical force in the propulsion phase (Figure 2), for each step after the blocks.

DISCUSSION: This study investigated force production during the first four steps in sprint running. The results from four runs of a single subject revealed gradually decreasing contact times while the flight times progressively increased from step to step (Table 1). The maximum horizontal braking force increased three fold from the first to fourth step. In the first step, it was clearly less than in Mero (1988) (-215 vs -316 N) showing that the current athlete was able to position the foot better for contact than the subjects in Mero's study, whose athletes were at a similar level to the current athlete at the group level (average personal best was 10.79 s ± 0.21 s for Mero's athletes). Mero et al. (1983) showed that the centre of mass stayed in the front of the contact point for the first two steps even though there was a braking phase, and moved behind the contact point only in the third step. Although video analysis was not carried out for the current study, the gradual increase of braking supports the previous finding. It is interesting, though, that time to reach this maximum value from the start of the contact stayed practically the same throughout each step. The reason for this might be that the braking may be passive in nature (note that in the propulsion phases the timings changed considerably). The influence of horizontal braking impulse on the athlete's velocity (Table 1) changed from -0.02 m/s in the first step to -0.06 m/s in the fourth step. At a later stage of sprinting (at the 16-m mark) Hunter et al. (2005) found that the influence of the braking impulse was -0.10 m/s. Although not directly comparable, these values seem to match well and show that the braking effect becomes gradually larger. This is also the case for the length of the braking in relation to the whole contact time. In Mero (1988) the braking lasted 11.4% of the first contact after the blocks. In the current study, the values were slightly lower: the respective value was 6.3% in the first step increasing to 9.9% in the fourth step. This can be assumed to increase further during the run, as it has been reported that the braking phase lasted 43% in the maximal sprinting phase (Mero and Komi, 1986).

A further clear difference between the results of this study and Mero (1988) occurred in the maximum vertical force in the first step (1477 vs. 739 N, respectively). Considering also the other maximum vertical force values (Figure 2), Mero's (1988) result seems to be quite low. It might be that the athlete in the current study came out from the blocks in such a way that he required lots of support in the first step. The clearly reduced maximum vertical force in the second step with gradual increase thereafter also implies this. Whether this is a general trend in modern sprinting or an individual technical issue for the current subject requires further investigation with other subjects. The gradual increase of the maximum vertical force from the second step forward is likely to be used to increase flight time (and consequently step length) between the steps. The increased flight time will require a slightly larger vertical movement of centre of mass (CM). The larger this movement, the more vertical force is required overall: first to stop downward movement at the start of the contact and then to thrust the CM enough vertically in the propulsion phase in order to stay in air long enough to increase the step length.

As the contact time reduced, so did the time to reach the maximum vertical force (Table 1). In the fourth step, the time was less than 50% of that in the first step despite the larger maximum force (Table 1 and Figure 2). This shows a considerably higher vertical force production rate requirement for the athlete in the latter steps. Despite large vertical force production, the current subject was able to produce comparable horizontal forces in the propulsion phase to that of Mero (1988). In the first step, the maximum horizontal forces were 852 vs. 788 N, respectively. Also, the net horizontal impulses were close at 94.0 vs 87 Ns. An athlete's acceleration is directly related to the net horizontal impulse, which showed a gradual decrease in this study (Figure 1). Based on these impulses, the athlete increased the horizontal velocity from the start of the first contact to the end of the fourth contact by 3.35 m/s, 3.35 m/s, 3.27 m/s and 3.38 m/s in each of the four runs. To calculate the overall velocity change from the impulse does not take air resistance into account. It can, however, be considered to be practically the same in each run, and thus these values yielded a remarkably similar increase in velocity (coefficient of variation was 1.4%) despite differences in some kinetic variables. It was not possible to provide data from individual runs within the scope of this article. However, the results revealed, for example, that an extended braking time in one step yielded a reduced braking time in the next step. This implies that if the foot was positioned badly to cause a longer braking, the increased time in the contact was possibly used to get other body parts to more favourable positions for the next step. It is, though, clear that there is not enough evidence to fully conclude this based on the current study. Thus, such neural control issues would be interesting topics for future studies. The work could also be expanded to calculate joint moments by combining video analysis and force information to reveal how the gradual change of emphasis from horizontal to vertical force is produced by athletes.

CONCLUSIONS: The only way the athlete can increase the horizontal velocity is via horizontal impulse. It is clear from this study that this impulse gradually decreases after leaving the blocks. This causes an optimisation problem for athletes, as larger horizontal forces may require a longer period of contact, which despite the increased impulse may take too long considering that in sprinting the competition is based on the shortest performance time. On the other hand, longer contacts at the start are not necessarily harmful, if the force can be kept at high level. Unfortunately from coaches' and athletes' point of view, this can only be found out using force platforms. The results in this study also revealed that the gradual decrease in horizontal impulse was transferred to a gradual increase in vertical force production to support the small but required vertical movement of CM.

REFERENCES:

Bates, B.T. (1996). Single subject methodology: An alternative approach. *Medicine and Science in Sports and Exercise,* 28, 631-638.

Dixon, S.J., & Kerwin, D.G. (2002). Variations in Achilles tendon loading with heel lift intervention in heel-toe runners. *Journal of Applied Biomechanics,* 18, 321-331.

Guissard, N., Duchateau, J., & Hainaut, K. (1992). Emg and mechanical changes during sprint starts at different front block obliquities. *Medicine and Science in Sports and Exercise,* 24, 1257-1263.

Henry, F. M. (1952). Force-time characteristics of the sprint start. *The Research Quarterly,* 23, 301-318.

Hunter, J.P., Marshall, R.N., & McNair, P. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics,* 21, 31-43.

Johnson, M.D., & Buckley, J.G. (2001). Muscle power patterns in the mid-acceleration phase of sprinting. *Journal of Sports Sciences,* 19, 263-272.

Kuitunen, S., Komi, P.V., & Kyröläinen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and Science in Sports and Exercise,* 34, 166-173.

Mero, A. (1988). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise and Sport,* 59, 94-98.

Mero, A., & Komi, P.V. (1986). Force-, EMG, and elasticity-velocity relationship at submaximal, maximal and supramaximal running speeds in sprinters. *European Journal of Applied Physiology and Occupational Physiology,* 55, 553-561.

Mero, A., Luhtanen, P., & Komi, P.V. (1983). A biomechanical study of the sprint start. *Scandinavian Journal of Sports Science,* 5, 20-28.

Schot, P. K., & Knutzen, K.M. (1992). A Biomechanical analysis of 4 sprint start positions. *Research Quarterly for Exercise and Sport,* 63, 137-147.

Weyand, P.G., Sternlight, D.B., Bellizzi, M.J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of Applied Physiology,* 89, 1991-1999.

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