CONTRIBUTIONS TO BRAKING IMPULSE DURING INITIAL ACCELERATION, TRANSITION AND MAXIMAL VELOCITY IN SPRINTING

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The aim of this study was to quantify the magnitude of braking impulse induced on the centre of mass by the accelerations at the foot-floor joint during steps three, nine and 19 of maximal sprinting. An induced acceleration analysis was performed to quantify the induced centre of mass accelerations. The accelerations at the foot-floor joint following touchdown generated -0.02 ± 0.01 $m.s^{-1}$ (143 ± 72%), -0.04 ± 0.01 $m.s^{-1}$ (80 ± 47%) and -0.07 ± 0.01 $m.s^{-1}$ (50 ± 13%) of the total relative braking impulse during steps three, nine and 19. A large portion of these foot-floor accelerations resulted from the deceleration of the foot at touchdown. The results suggest that minimising horizontal foot velocities prior to touchdown will result in reduced braking forces. Further research is required to empirically investigate this mechanism in an applied setting.

KEY WORDS: Induced Acceleration Analysis, braking forces, foot velocity

INTRODUCTION: During sprinting, the change in horizontal velocity is determined by the magnitude of the net horizontal impulse (IMP_H) sprinters generate during ground contact (Hunter, Marshall & McNair, 2005; Morin, Slawinski, Couturier, Samozino, & Rabita, 2015). Since the braking (IMP_{H-}) and propulsive (IMP_{H+}) impulses sprinters generate determine the net horizontal impulse, sprinters can modulate their net impulse by manipulating the braking and propulsive impulses independently (Morin et al., 2015). Previous literature suggested that sprinters could maximise performance by aiming to minimise the braking forces generated during ground contact (Mann & Sprague, 1983; Hay, 1994). It has been suggested that sprinters should minimise the horizontal velocity of the foot immediately prior to touchdown (Mann & Sprague, 1983) with the horizontal velocity of the foot prior to touchdown described as the main determinant of a braking force (Hay, 1994). Hunter et al. (2005) showed that during sprint acceleration, a smaller forwards horizontal foot velocity prior to touchdown was associated with lower braking forces. Unless the velocity of the foot is close to zero prior to touchdown, the foot of the sprinter will undergo rapid deceleration at touchdown, which could result in generating a negative horizontal ground reaction force and therefore IMP_{H-}. There is currently a lack of empirical evidence quantifying the contribution of foot velocity to IMP_{H-}. The aim of this study was to quantify the magnitude of IMP_{H-} generated by the accelerations at the foot-floor interface (foot-floor_{acc}) after touchdown.

METHODS: Ten experienced male sprinters (75.1 ± 3.4 kg, 1.78 ± 0.05 m, 100 m PB: 10.85 ± 0.30 s) gave written informed consent to participate in the study. Ground reaction forces (GRF) and kinematic data were collected from steps three, nine and 19 during maximal sprints from blocks. Up to three trials per athlete were completed for each step where the starting line was placed 3 m, 13 m and 33 m, respectively, from two force plates (1000 Hz; Kistler type 9827CA, Kistler Instruments AG, Winterthur, Switzerland) operated by Codamotion analysis (Charnwood Dynamics Ltd, UK). One mini DV digital camera (Sony Z5) was set up 15 m from the centre of the running lane and a 4.00 m × 1.90 m plane was calibrated. The camera recorded images at full resolution (1440 × 1080) at 200 Hz with an open iris and a shutter speed of 1/600 s. The video and force plate data were synchronised to the nearest 0.001 s using a series of illuminating LEDs (Wee Beastie, UK).

The videos were digitised using an 18-point model, reconstructed using a 9-parameter 2D-DLT and then filtered using a 4th order Butterworth filter with a 26 Hz cut-off frequency. The body was represented using five segments (forefoot, rear foot, shank, thigh and HAT (head, arms and trunk)) for which data from de Leva (1996) were used to calculate the inertia data for all the segments except the foot. For the foot segments, inertia data from Bezodis, Salo & Trewartha (2014) was used with the mass of the sprint shoe added. The horizontal velocity of the foot (immediately before touchdown) and touchdown distance (horizontal distance between the centre of mass and metatarso-phalangeal (MTP) joint at touchdown) were identified. Ground contact was identified using a 10 N threshold in vertical GRF before being down sampled to 200 Hz and filtered with a 4th order low pass Butterworth filter with a 26 Hz cut-off frequency. Joint moments were calculated according to Winter (2005). The forefoot segment and MTP joint were included in the calculation when the centre of pressure (COP) was in front of the MTP joint (Stefanyshyn & Nigg, 1997). The best step three, nine and 19 trial was selected for further analysis. This was based on the highest horizontal external power (Bezodis, Salo & Trewartha, 2010) for steps three and nine, whilst the best step 19 trial was based on the highest step velocity.

Contributions to centre of mass (CM) acceleration were determined by performing an induced acceleration analysis (IAA) according to Hof & Otten (2005). A linear equation (c=A*x; Hof & Otten, 2005) was set-up. The (n × n) matrix A represents the Newton-Euler equations describing the motion of the segments and constraint equations, which enforce matched accelerations of adjacent segments. Three discrete points were used to describe the ground contact point throughout stance. These included the horizontal positions of the MTP, distal hallux (toe) and the COP. When the MTP and toe heights fell below a vertical threshold level (i.e. below the minimum measured height during ground contact + 0.010 m), the ground contact points were defined at the horizontal position of the MTP and toe. During this time, a foot-floor joint was created between the CM of the forefoot and the MTP and between the CM of the forefoot and the toe ground contact points. Otherwise, the ground contact point was defined at the COP were a foot-floor joint was defined between the most distal segment and the COP. The most distal segment was either the forefoot or the rear foot depending on the location of the COP. Constraint equations (Equation 1 & 2) were included which keep the foot constrained to the ground:

$$foot\text{-}floor_{acc}(y) = a_{1y} - \alpha_1(r_{dz1}) - \omega_1^2(r_{dy1}) = 0 \qquad [1]$$

$$foot\text{-}floor_{acc}(z) = a_{1z} + \alpha_1(r_{dy1}) - \omega_1^2(r_{dz1}) = 0 \qquad [2]$$

where $foot\text{-}floor_{acc}$ represent the accelerations at the foot-floor contact joints. These were calulated from the known linear (a_1) and angular (α_1) accelerations and angular velocity (ω_1) of the segment connected to the ground. The vectors r_{d1} represent the horizontal and vertical distance from the CM of the segment to the contact joint. The linear equation c=A*x was solved by inverting A to give x = A^{-1}·c. The (n × 1) vector c included the inputs including joint moments (jm), gravity (g), centripetal accelerations of the stance leg joints (ca) and foot-floor$_{acc}$. The individual contributions to CM acceleration were obtained separately. The outputs (x) include segment linear and angular accelerations, intersegmental forces and GRF. Total contributions to CM accelerations were calculated by summing the individual contributions. The IMP$_{H-}$ during the braking phase of ground contact was calculated via integration (trapezium rule) of the measured CM acceleration, total induced CM accelerations as well as the individual contributors to CM acceleration.

Contributions by jm, g and ca were combined and represented as 'other' contributions. The accuracy of the analysis was determined by calculating the absolute and relative (i.e. relative to the measured IMP$_{H-}$) root-mean-square difference (RMSD) between the measured IMP$_{H-}$ and calculated total IMP$_{H-}$. Data are presented as mean ± standard deviation (SD).

RESULTS and DISCUSSION: Using an IAA, the specific contributions to total IMP$_{H-}$ during steps three, nine and 19 were quantified. The accuracy of the analysis between the total calculated and measured IMP$_{H-}$ revealed differences of 0.00 - 0.01 m.s^{-1} or 5 - 13% of the measured IMP$_{H-}$. During the braking phases of ground contact, the IMP$_{H-}$ created by the foot-floor$_{acc}$ increased from steps three to nine to 19 (Table 1). This was mostly due to the deceleration of the most distal segment (component a_1 from equations 1 & 2) following touchdown, which contributed 120 ± 28%, 103 ± 10%, and 98 ± 6% of the foot-floor$_{acc}$ IMP$_{H-}$ during steps three, nine and 19, respectively. These coincided with increasing horizontal foot velocities prior to touchdown (Table 1). Although total IMP$_{H-}$ is not strongly related to sprint performance during the early phases in sprinting (Hunter et al., 2005; Morin et al., 2015), previous studies have highlighted that net IMP_H decreases due to both an increasing IMP_{H-} and decreasing IMP_{H+} (Morin et al., 2015; Nagahara, Mizutani & Matsuo, 2016) during the transition phase. During the maximal velocity phase (step 15 onwards), the increasing IMP_{H-} was the main factor contributing to the decreasing net IMP_H (Nagahara et al., 2016). The results of this study suggest that minimising the horizontal foot velocity prior to touchdown plays an important role in minimising foot-$floor_{acc}$ at touchdown and therefore IMP_{H-}. This could benefit performance especially at higher running velocities.

Table 1: Mean ± SD pre-touchdown horizontal foot velocity (FV_h), touchdown (TD) distance and IMP_{H-} generated by foot-$floor_{acc}$

	FV_h [$m.s^{-1}$]	TD distance [m]	Foot-$floor_{acc}$ IMP_{H-} [$m.s^{-2}$]
Step 3	0.57 ± 0.91	0.04 ± 0.06	-0.02 ± 0.01
Step 9	2.09± 0.95	0.26 ± 0.06	-0.04 ± 0.01
Step 19	2.51 ± 0.62	0.35 ± 0.05	-0.07± 0.02

The current investigation revealed that during the braking phases of steps three, nine and 19, the foot-$floor_{acc}$ was not the only contributors to total IMP_{H-} (Fig: 1). While 143 ± 72% of the total IMP_{H-} was generated by the foot-$floor_{acc}$ during step three, only 80 ± 47% and 50 ± 13% of the of the total IMP_{H-} can be accounted for by the foot-$floor_{acc}$ during steps nine and 19. The 'other' contributors (Figure 1) therefore play an increasingly larger role increasing total IMP_{H-} during transition and maximal velocity. The 'other' contributions to total IMP_{H-} were negative during step three (-43 ± 72%) and positive during steps nine (20 ± 47%) and 19 (50 ± 13%). During step three, the 'other' contributors acted to minimise the IMP_{H-} generated by the foot-$floor_{acc}$ while during steps nine and 19 the 'other' contributors added to the IMP_{H-} generated by the foot-$floor_{acc}$. This may be due to the changes in postural variables (e.g. touchdown distance) between steps three, nine and 19 (Table 1), with larger braking impulse associated with larger touchdown distances (Hay, 1994; Hunter et al., 2005). Since the orientation of the segments dictate the direction of the induced accelerations (Hof & Otten, 2005), the larger touchdown distance and more vertical orientation of the segments will have influenced the direction of the accelerations induced by the 'other' sources and therefore contributed to the IMP_{H-} of steps nine and 19.

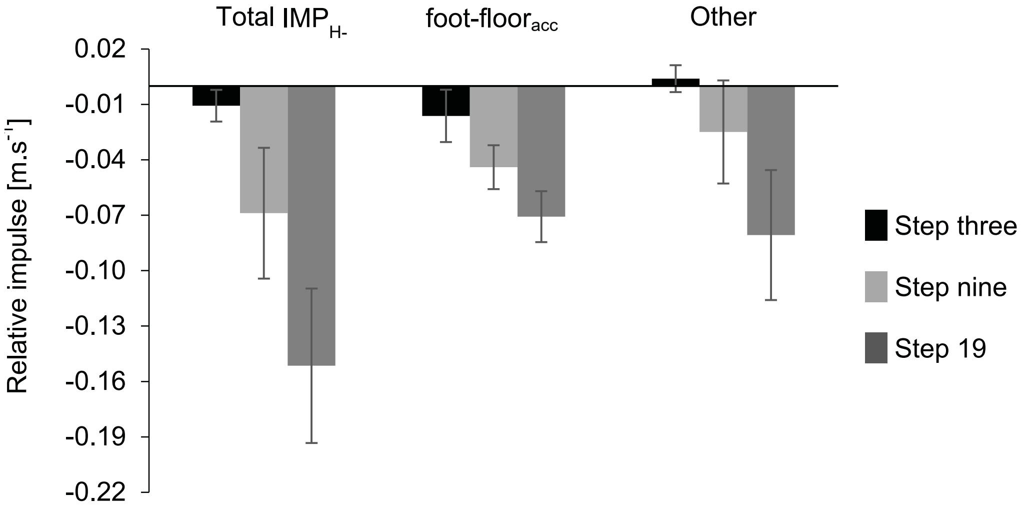

Figure 1: Mean ± SD total IMP_{H-} and contributors to total IMP_{H-} including foot-$floor_{acc}$ and 'other' sources.

These results provide empirical evidence showing the effect that the deceleration of the foot at touchdown has on IMP_{H-} and supports the proposal by previous authors that sprinters should minimise the forward velocity of the foot prior to touchdown in order to reduce IMP_{H-} during stance (Mann & Sprague, 1983; Hunter et al., 2005). This suggestion should however be treated with caution, it could be speculated that attempting to increasingly minimise foot velocity, especially during high velocity sprinting, may increase the risk of hamstring injuries. Furthermore, minimising horizontal velocity of the foot prior to touchdown may have a detrimental impact on vertical GRF, which could be detrimental to performance during the maximal velocity phase. Lastly, although not directly quantified in this study, these results suggest that changes in posture (e.g. touchdown distance) between steps three, nine and 19 may have influenced the 'other' contributions to total IMP_{H-}. Futher analysis is required to identify how posture influences both the horizontal and vertical impulses during stance. A sensitivity analysis, during which either foot velocity or posture (segment orientations) are changed systematically, could provide an initial understanding about how changes in either foot velocity or posture impact horizontal and vertical GRF.

CONCLUSION: This study showed that a major component of the total IMP_{H-} during steps three, nine and 19 was contributed by the foot-floor$_{acc}$. This was largely due to the deceleration of the foot at touchdown. A larger deceleration is required when the forward velocity of the foot prior to touchdown was higher, which in turn results in a greater IMP_{H-}. Touchdown distance may have played a role in increasing total IMP_{H-} during steps nine and 19. While the results suggest that minimising horizontal foot velocities prior to touchdown will result in reduced braking forces, further research is required to understand the influence of decreasing horizontal foot velocities on the incidence of hamstring injury during high velocity sprinting.

REFERENCES:

Bezodis, N. E., Salo, A. I., & Trewartha, G. (2010). Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: which is the most appropriate measure?. Sports Biomechanics, 9(4), 258-26

Bezodis, N. E., Salo, A. I. T., & Trewartha, G. (2014). Lower limb joint kinetics during the first stance phase in athletics sprinting: three elite athlete case studies. Journal of Sports Sciences, 32(8), 738-746.

de Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*, 1223-1230. doi: 10.1016/0021-9290(95)00178-6

Hay, J. G. (1994). The biomechanics of sports techniques (4th ed.). London: Prentice Hall International.

Hof, A. L., & Otten, E. (2005). Assessment of two-dimensional induced accelerations from measured kinematic and kinetic data. *Gait & Posture*, 22(3), 182-188.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. Journal of Applied Biomechanics, 21(1), 31-43.

Mann, R., & Sprague, P. (1983). Kinetics of sprinting. In ISBS-Conference Proceedings Archive (Vol. 1, No. 1).

Morin, J. B., Slawinski, J., Dorel, S., Couturier, A., Samozino, P., Brughelli, M., & Rabita, G. (2015). Acceleration capability in elite sprinters and ground impulse: Push more, brake less?. Journal of Biomechanics, 48(12), 3149-3154.

Nagahara, R., Mizutani, M., & Matsuo, A. (2016). Ground reaction force of the first transition during accelerated sprinting: a pilot study. International Society of Biomechanics in Sports Conference Proceedings, 26, 859-862. Retrieved from https://ojs.ub.uni-konstanz.de/cpa/article/view/1912/1781

Stefanyshyn, D. J., & Nigg, B. M. (1997). Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. Journal of Biomechanics, 30(11-12), 1081-1085.

Winter, D.A. (2005). *Biomechanics and Motor Control of Human Movement*. Hoboken: John Wiley and Sons, Inc.

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