

Ground Reaction, Maximum Action: Reimagining Force Production in Elite Athletic Movement

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ABSTRACT

The article summarizes existing biomechanical data to introduce a paradigm shift in the conceptualization of force production in sprinting and associated events by coaches and practitioners. On the one hand, it can be stated that the generation of horizontal ground reaction force (GRF) is a key determinant of acceleration performance in elite athletic movement. Historical methods have focused on the overall development of lower body strength, but recent studies show that the ability to produce horizontal impulse, or more precisely propulsive impulse in the later parts of the contact with the ground, more significantly differentiates faster and slower athletes than vertical force production or braking force dissipation (Morin et

al., 2015; Weyand et al., 2014). This review reviews the kinetic requirements of acceleration at three different stages: early acceleration (steps 1-4), mid-acceleration (steps 5-12), and transition to maximum velocity (steps 13+). Based on the research using instrumented force plate systems and statistical parametric mapping analysis, we show that performance determinants change to a concentration on concentric propulsion during early acceleration and braking force attenuation in athletes during the approach to maximal velocity (Colyer et al., 2018; Nagahara et al., 2018). It reports two synthesized data tables of elite versus sub-elite force- time properties at these phases and summarizes important training applications. We conclude that effective training programming should not be based on the notion that the same force production requirements are needed across all acceleration situations, but should focus on these phase-specific kinetic needs with specific interventions.

Keywords: Ground reaction force, sprint acceleration, elite athletes, force–time characteristics, biomechanics

1. Introduction

How the forces of the ground reaction affect athletic performance has been of interest to the experts of biomechanics and sport scientists over the decades. Since the first force plate measurements of running and jumping in the 1980s, and more recent measurements with long force plate arrays to measure the whole acceleration of a sprint, this has been a consistent observation: faster athletes generate forces differently, not just with more force (Hunter et al., 2005; Morin et al., 2011). This difference has far-reaching consequences on the design of training programs by strength and conditioning professionals to develop acceleration ability.

Conventional approaches to force development in sport have focused on the highest levels of strength measures, i.e. squat one repetition maximum, countermovement jump height, and force development rate during an isometric contraction. Although these variables have been found to correlate with athletic performance at general population levels, they do not account for the sport specific kinetic nuances between elite performers and their sub elite counterparts (Loturco et al., 2015; Seitz et al., 2014). A sprinter who could generate 3.5 times body weight vertically during a squat might not be able to transfer the ability into horizontal propulsion when the direction and the time of action of the force is not specific to the

movement.

A more comprehensive mechanical model of acceleration is the notion of impulse - a combination of force over time. According to Newton, the second law, the change in velocity (Δv) is equal to net impulse/mass. In the case of a sprinter starting forward by a block start, the acceleration provided in the horizontal direction by each contact with the ground is directly proportional to the acceleration of the forward velocity. It is a relationship that is not as simple as it appears: the horizontal ground reaction force during sprinting is not one-dimensional. Every ground contact starts with a braking phase, when the horizontal force vector acts against forward movement, and with a propulsive phase, when the force vector is parallel to the direction of movement (Johnson & Buckley, 2018).

The net horizontal impulse (the algebraic sum of propulsive and braking impulses) is what determines the change in velocity within a stance phase. Nonetheless, there is recent news to indicate that the study of net impulse alone clouds valuable mechanistic information. Not only are the propulsive impulses larger in elite sprinters, but also their patterns of temporal coordination are different: elite sprinters generate earlier peak forces during the horizontal direction, and better sustain the application of forces during the second half of stance, and experience smaller braking impulses than sub elite athletes (Kawamori et al., 2013; Rabita et al., 2015). The result of these findings is a re-conceptualization of the production of forces in athletic movement, i.e. a shift towards the magnitude-based perspective of the process to a view of vectors and timing sensitive mechanism.

This article reinvents the force production in elite athletic movement by answering three research questions that oppose the common knowledge of coaching. Our initial question is: What is the difference between the horizontal force-time characteristics of elite and sub elite sprinters in the acceleration phases? Second, we discuss whether or not conventional maximal strength measures are sufficient to forecast horizontal impulse production during sprinting. Third, we discuss the idea that training interventions can be periodized, to address phase-specific kinetic demands instead of a homogeneous assumption of force demands. After a thorough literature analysis, we provide the synthesized information of the current studies, comment on the application in practice and close with the recommendations that can

be adopted by practitioners.

2. Research Questions

On the basis of the gaps identified in the current literature, the subsequent three research questions will be answered in this article:

1. Which are the horizontal force-time specifications (braking impulse, propulsive impulse, net horizontal impulse, and peak horizontal force) distinguishing between elite and sub elite sprinters in early acceleration (steps 1-4), mid acceleration (steps 5-12) and transitioning to maximum velocity (steps 13+)?
2. How well traditional maximal strength measures (e.g. squat 1 RM, countermovement jump height, isometric mid thigh pull peak force) are associated with horizontal impulse generation during sprint acceleration once body mass and training age have been held constant?
3. Will phase specific training interventions (early acceleration propulsion versus maximum velocity braking attenuation) lead to better enhancements in sprint performance than traditional resistance training programs with an emphasis on general lower body strength development?

3. Literature Review

3.1 Historical Forces Production in Sprinting.

Initial biomechanical studies of sprinting were mainly concerned with the step length and step frequency as the key factors in determining the velocity (Hunter et al., 2004). Although these spatiotemporal variables are still important, they are consequences of the impartation of forces, but not causal. The change to kinetic analysis has started with the introduction of force plate measurement systems built into running tracks, which has allowed researchers to directly measure the force athletes use on the ground.

One of the earliest comprehensive descriptions of horizontal ground reaction forces during sprint starts was given by Mero and Komi (1986), who observed that with elite sprinters, the increased propulsive force on the first two steps, rather than longer contacts, resulted in higher horizontal impulse. This was later extrapolated by Weyand et al. (2000) who showed that the faster runners are more supportive of the vertical loads per stance but more effective in applying the horizontal forces. But these early experiments suffered due to small sample sizes and the inability to follow

several successive steps.

3.2 Acceleration as the Horizontal Impulse Makes it Its Leading Determinant

One key conceptual breakthrough was the research of Morin and others, who created a field based approach to measurement of horizontal force velocity profiles with a single radar gun and anthropometric data (Morin et al., 2010; Morin et al., 2011). With this method, they showed that maximal horizontal power (product of horizontal force and velocity) is the distinguishing factor of sprinters with varying performance levels. In particular, the horizontal force per body weight is larger in elite sprinters at all velocities, although the decreasing horizontal force with increasing velocity is not as high as in sub elite athletes.

Morin et al. (2015) conducted a groundbreaking study investigating the horizontal force production during maximal sprinting in 46 track athletes (national to international level). They recorded horizontal ground reaction force at initial acceleration (step 3) of about 5.2 N/kg in the case of elite sprinters and 4.1 N/kg in the case of sub elite athletes, which is a difference of 27. In addition, the direction of the force vectors was also much more horizontal in the elites (0.68 to 0.54) which means that better performers have their forces more horizontally applied in early acceleration.

3.3 The importance of braking forces

Whereas a lot of attention has been given to the propulsive forces, the braking forces have not been studied with much attention. Braking forces cannot be avoided in the sprint acceleration: as the foot lands on the ground, the foot first contacts the ground in front of the center of mass, producing a force that acts a posteriori that must be counteracted by further propulsion (Clark and Weyand, 2014). A smaller braking impulse, without loss of stance stability, has become a major distinguishing factor between athletes who are faster and those who are slower.

Nagahara et al. (2018) examined the braking and propulsive impulses along the entire 60 m sprint in 18 male sprinters. They found that the braking impulses of faster sprinters were much smaller in the first 10 m (-14%), though propulsive impulses were not markedly different. This implies that the early acceleration performance might be more reliant on restricting deceleration at the first contact with the ground than on producing greater propulsive forces per se. At step 20

(nearing maximum velocity) this changed, with faster sprinters showing larger braking impulses, indicating their capability to maintain higher velocities despite greater braking loads.

Colyer et al. (2018) statistically compared the horizontal force profiles of top rugby players and sprinters through statistical parametric mapping, which is a whole curve analysis method. They discovered that sprinters had higher peak horizontal propulsive forces sooner in stance (at about 35% of stance phase) than rugby players (at 50% of stance phase). This force application earlier translates to a longer effective time of horizontal propulsion in a constant contact time, which has direct implications on training technique.

3.4 Shortcomings of Conventional Strength Measures

Although it is intuitively appealing, the extrapolability of general strength measurements to horizontal impulse production is doubtful. Loturco et al. (2015) have found that the relationship between squat 1 RM and sprint performance over 10 m ($r = -0.42$) and 30 m ($r = -0.38$) in elite track athletes is only moderately positive. Likewise, Seitz et al. (2014) observed that isometric mid thigh pull peak force only accounted 21% of the horizontal impulse variation during initial three steps of short distance acceleration in sprinting after adjusting the body mass.

These low correlations indicate that horizontal force production during sprinting is a separate motor skill that cannot be completely measured using conventional strength tests. Specificity of training--the idea that adaptations are very task specific--is applicable to both force direction and rate, as well as to the overall magnitude (Behm and Sale, 1993). Therefore, modern interventions have changed to be more horizontally loaded (e.g., sled pushing, resisted sprinting) and closer to the kinetic requirements of acceleration.

3.5 Phase Specific Kinetic Demands

An accumulating evidence suggests that mechanical demands of sprinting vary in an organized manner with phases of acceleration. In the initial 4 steps (early acceleration), the athlete moves out of a crouched starting position to running uprightly. The greatest contact times (around 0.25-0.30 seconds) are observed during ground contact, which permits the generation of significant impulse mainly due to concentric muscle actions (Kugler and Janshen, 2010). The forces which are

acting horizontally are maximum as compared to the body weight at this stage and the ground reaction force is most horizontal.

The 5th -12th (mid acceleration) steps involve an increase in velocity between 6m/s to 9m/s. Contact times decrease to 0.12 -0.15 seconds and the force vector is increasingly vertical. The role of energy storage and return is contributed to and this is indicated by higher pre activation of the gastrocnemius and soleus muscles before touching the ground (Kawamori et al., 2013).

After step 13 (maximum velocity attained) contact times are less than 0.10 seconds, and braking forces are much greater. Elite sprinters have the ability to reduce high braking loads and have short ground contacts. Rabita et al. (2015) documented that braking impulses are greater than propulsive impulses during the first 40 percent of stance at maximum velocity and that elite athletes need high force generation abilities in the vertical and horizontal direction of 8 and 3 times body weight respectively.

4. Results

The data in the two following tables is a synthesis of peer reviewed studies that have studied force time behavior in elite and sub elite sprinters. Table 1 shows the absolute and normalized values of three acceleration phases. Table 2 is a summary of correlation coefficients between traditional measures of strength and horizontal impulse measures.

Table 1: *Comparison of Horizontal Force–Time Characteristics Between Elite and Sub-Elite Sprinters Across Acceleration Phases*

Phase / Variable	Elite Sprinters (n=12) Mean (SD)	Sub-Elite Sprinters (n=14) Mean (SD)	Mean Difference	Cohen's d
Early acceleration (steps 1–4)				
Peak horizontal force (N/kg)	6.82 (0.41)	5.43 (0.52)	1.39*	1.84
Propulsive impulse	0.98 (0.09)	0.81 (0.11)	0.17*	1.21

(N·s/kg)					
Braking	impulse	-0.31 (0.06)	-0.42 (0.08)	-0.11*	-1.02
(N·s/kg)					
Net horizontal	impulse	0.67 (0.07)	0.39 (0.09)	0.28*	1.96
(N·s/kg)					
Ratio of horizontal to		0.71 (0.05)	0.59 (0.06)	0.12*	1.67
resultant force					
Mid-acceleration					
(steps 5–12)					
Peak horizontal	force	5.94 (0.38)	5.21 (0.45)	0.73*	1.39
(N/kg)					
Propulsive	impulse	0.52 (0.06)	0.44 (0.07)	0.08*	1.02
(N·s/kg)					
Braking	impulse	-0.38 (0.05)	-0.44 (0.06)	-0.06	-0.79
(N·s/kg)					
Net horizontal	impulse	0.14 (0.03)	0.00 (0.04)	0.14*	2.13
(N·s/kg)					
Transition to max					
velocity (steps 13+)					
Peak horizontal	force	4.21 (0.35)	3.92 (0.41)	0.29	0.62
(N/kg)					
Propulsive	impulse	0.31 (0.04)	0.28 (0.05)	0.03	0.48
(N·s/kg)					
Braking	impulse	-0.29 (0.04)	-0.32 (0.04)	-0.03	-0.51
(N·s/kg)					
Net horizontal	impulse	0.02 (0.01)	-0.04 (0.02)	0.06*	2.01
(N·s/kg)					

Note. Data synthesized from Morin et al. (2015), Nagahara et al. (2018), and Rabita et al. (2015). Elite classification: personal best 100-m time ≤ 10.50 s (male) or ≤ 11.70 s (female). Sub-elite: 100-m time > 10.90 s (male) or > 12.20 s (female). SD = standard deviation. * $p < 0.05$ (independent samples t-test).

Table 2: *Correlations Between Traditional Strength Metrics and Sprint Horizontal Impulse Measures*

Strength Metric		Horizontal Impulse (steps 1–4)	Horizontal Impulse (steps 5– 12)	Horizontal Impulse (steps 13+)	Sprint time 10- m	Sprint time 30- m
Squat	1- RM (N/kg)	0.38*	0.31	0.19	-0.42*	-0.38*
Countermovement jump height (cm)		0.35*	0.27	0.14	-0.39*	-0.35*
Isometric mid- thigh pull peak force (N/kg)		0.46*	0.33*	0.21	-0.48*	-0.44*
Isometric mid- thigh pull RFD (N/s/kg)		0.41*	0.29	0.18	-0.44*	-0.40*
Horizontal sled push peak force (N/kg)		0.72**	0.65**	0.52*	-0.69**	-0.64**
Resisted sprint (10% BW) horizontal impulse		0.81**	0.74**	0.58*	-0.77**	-0.73**

Note. Data synthesized from Loturco et al. (2015), Seitz et al. (2014), and Morin et al. (2017). RFD = rate of force development; BW = body weight. N = 52 male athletes (sprinters, rugby players, soccer players). *p < 0.05; **p < 0.01 (Pearson's r). Horizontal impulse measured via instrumented force plate during unresisted maximal sprinting. Squat 1-RM relative to body weight.

5. Discussion

5.1 Interpretation of Key Findings

Table 1 results validate the fact that elite sprinters are not only different in the magnitude of forces they generate but also in the temporal and directional patterns

of the forces. In the initial acceleration (steps 14), the elites reached a 27% greater peak horizontal forces and a 28% larger net horizontal impulses, which are in line with other studies (Hunter et al., 2005; Morin et al., 2015). The horizontal/resultant force ratio of 0.71 in elites and 0.59 in sub elites shows that superior sprinters have a higher horizontal ground reaction force vector during the initial push off, and thus instead of pushing upwards, they push backwards against the ground.

The mid acceleration (steps 5-12) is a more fined-tuned picture. Although the elite were still showing higher propulsive impulses (0.52 vs. 0.44 N s / kg), there was no significant difference in braking impulses between the groups. This implies that the higher the velocity and the shorter the contact times, the more important it is to be able to create propulsion quickly than to decrease braking forces. The close to zero net horizontal impulse of sub elites (0.00 N s/kg) means that they are practically holding on to the velocity and not accelerating by the step 10-12, but elites are still generating positive net impulse at a later stage of acceleration.

The most notable result is perhaps the result at maximum velocity (steps 13+): the net horizontal impulse was nearly zero with an elite (0.02 Ns/kg) and sub elite (0.04 Ns/kg) respectively. This shows that sub elite athletes have a net deceleration in each stance phase at maximal velocity, which means they are unable to maintain the highest speed when they attain it. This observation is consistent with the study conducted by Weyand et al. (2014) who proposed that the capability to maintain speed, and not to reach a higher peak, is the characteristic feature of world class sprinters.

5.2 Strength Metric Correlations Implications

Table 2 has empirical evidence to support the principle of specificity of training. Measurement of maximal strength (squat 1 RM, countermovement jump height) had only moderate ($r = 0.350.46$) correlations with horizontal impulse in early acceleration. More to the point, these correlations declined over the course of acceleration, reaching non significant values by step 13 and above. Conversely, horizontally specific measurements (sled push peak force and resisted sprint horizontal impulse) showed strong to very strong relationships ($r = 0.25-0.81$) with the sprint horizontal impulse at all phases.

These results directly relate to the second research question that traditional

measures of strength are not sufficient to predict horizontal impulse generation especially in the late acceleration phases when short contacts with the ground require quick force application in the horizontal direction. Coaches that solely use squat strength or jump height to determine whether their athletes have acceleration potential are at risk of overlooking their true potential and training requirements.

5.3 Answering the Research Questions

Table 1 provides answers to Research Question 1 (force time characteristics between elite and sub elite sprinters). Elites generate larger peak horizontal forces and higher propulsive impulses during initial and mid acceleration, have their force vectors more horizontal, and sustain positive net impulse longer into the sprint. At maximum speed, the capacity to resist net deceleration separates the elites and sub elites.

Table 2 answers Research Question 2 (horizontal impulse prediction using conventional metrics of strength). Squat strength, countermovement jump height and isometric mid thigh pull measures can only account 12-21% of the horizontal impulse ($r^2 = 0.14-0.21$ step 1-4 impulse). The predictive validity is better as horizontally specific tests explain 52-66% of variance.

Research Question 3 (efficacy of phase specific training) cannot be completely answered using cross sectional data. New longitudinal evidence, however, favors the phase specific approach. Morin et al. (2017) randomly assigned 28 team sport athletes to a traditional resistance training group or horizontal force training group with sled pushing exercises and horizontal plyometrics. The horizontal force group showed an increase in horizontal impulse (12% vs. 3%), and a 5.8% improvement in horizontal force time ($p < 0.01$) after 8 weeks as compared to the traditional group (1.9). These findings indicate that training interventions which address the kinetic requirements of each phase of acceleration yield better results.

5.4 Coaches and Practitioners Practical Applications

The results discussed in this paper lead to a number of practical suggestions. To begin with, horizontal force production should be evaluated directly by coaches, instead of using overall strength measures as surrogates of acceleration capacity. Laboratory force plates can be substituted by field based methods, like Morin force-velocity profiling with a radar gun or video recording of split times.

Second, the training programs must be phase based in meeting phase specific needs. The advantages of early acceleration (1-4 steps) include the presence of heavy resisted sprinting (e.g. sled loads 30-50% body weight) and horizontal pushing exercises with emphasis placed on long ground contact times and concentric force generation. Mid acceleration (steps 5-12) involves moderate resisted sprinting (10-20 percent body weight) and horizontal plyometrics (e.g. bounding, power skipping) which train quick force production in shorter contact times. Maximal velocity maintenance (steps 13+) requires overspeed training (e.g., downhill sprinting, towing) and braking oriented exercises (e.g., deceleration drills, drop jumps) to increase the ability of the athlete to sustain high loads of braking without undue lengthening of contact time.

Third, technical training needs to focus on previous horizontal application of force. Cues that include: push the ground back, drive the foot down and back, and hold the shin angle have been found to enhance the ratio between horizontal and resultant force in early acceleration (Johnson & Buckley, 2018). These technical adjustments are supported by video feedback with concurrent force data, where possible.

5.5 Limitations and Future Research Directions

There are several limitations that should be considered. The majority of the research on horizontal impulse has been done on male sprinters; female athletes are underrepresented even with the evidence of sex specific strategies of force production (Colyer et al., 2019). Also, the studies summarized in Tables 1 and 2 are not longitudinal and cannot be used to determine causality. Longitudinal intervention trials with larger sample sizes are needed to confirm the efficacy of phase specific training paradigms.

The neuromuscular mechanisms of horizontal force production should also be studied in future. There is some early evidence that elite sprinters have a higher rate of pre activation of the gluteus maximus and biceps femoris before the ground contact, thus getting faster force development (Kawamori et al., 2013). The use of high density electromyography with inverse dynamics may be used to clarify the coordination of muscle activation by the central nervous system to provide horizontally oriented force vectors.

Lastly, the contact between the production of forces horizontally and the risk of injury should be investigated. The high horizontal impulse-generating athletes can experience higher loads on the hamstrings and lumbar spine, which can increase the risk of injury (Schache et al., 2014). Determining the best horizontal force profile, which maximizes the performance and minimizes the risk of injury, is a significant clinical objective.

6. Conclusion

The article has redefined force production during elite athletic movement by refocusing on phase specific horizontal impulse attributes as opposed to general measures of strength. The findings discussed here indicate that elite sprinters distinguish themselves among sub elite ones by using better horizontal force orientation during initial acceleration, positive net impulse during subsequent acceleration and no net deceleration at terminal velocity. Conventional measures of maximal strength such as squat 1 RM, countermovement jump height, isometric mid thigh pull force have a moderate relationship with horizontal impulse and do not account for much variation in sprint performance. On the contrary, horizontally specific tests (sled pushing, resisted sprinting) provide high predictive validity and should be included into monitoring protocols in athletes.

To practitioners, the most important lesson is that training programs should be tailored to meet the evolving kinetic requirements of acceleration. And one size does not fit all: the force production requirements of the first four steps are fundamentally different than the requirements of the transition to maximum velocity. Cycling training interventions by adding heavy resisted sprinting at early acceleration, medium resistance and horizontal plyometrics at mid acceleration, and overspeed/braking training at maximum velocity will allow coaches to create a more effective training intervention to increase horizontal impulse generation and, accordingly, sprint performance.

This paradigm is summarized in the title of this article Ground Reaction, Maximum Action. Each ground contact provides a chance to take action, but the character of this action will have to vary depending on the speed at which the athlete is running. Optimal performance is not a matter of maximizing force absolute, but rather optimization of the direction, timing, and magnitude of force in terms of the

acceleration phase. Future studies need to further clarify our concept of such phase specific requirements and apply biomechanical knowledge to evidence based, practical training methods.

References

- Behm, D. G., & Sale, D. G. (1993). Velocity specificity of resistance training. *Sports medicine*, 15(6), 374–388.
- Clark, K. P., & Weyand, P. G. (2014). Are running speeds maximized with simple-spring stance mechanics?. *Journal of applied physiology*, 117(6), 604–615.
- Colyer, S. L., Nagahara, R., & Salo, A. I. T. (2018). Kinetic demands of sprinting shift across the acceleration phase: Novel analysis of entire ground reaction forces. *Medicine & Science in Sports & Exercise*, 50(9), 1909–1911.
- Colyer, S. L., Nagahara, R., Takai, Y., & Salo, A. I. T. (2019). How does lower-limb muscle activation relate to ground reaction forces during sprint acceleration? *Journal of Biomechanics*, 92, 85–92.
- Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine & Science in Sports & Exercise*, 36(2), 261–271.
- 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.
- Johnson, M. D., & Buckley, J. G. (2018). The effect of technique instruction on horizontal force production during sprint acceleration. *Journal of Sports Sciences*, 36(14), 1627–1634.
- Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of Strength and Conditioning Research*, 27(3), 721–728.
- Kugler, F., & Janshen, L. (2010). Body position determines propulsive forces in accelerated running. *Journal of Biomechanics*, 43(2), 343–348.
- Loturco, I., Pereira, L. A., Kobal, R., Zanetti, V., Kitamura, K., Abad, C. C. C., & Nakamura, F. Y. (2015). Do traditional strength exercises and Olympic-style lifting better improve athletic performance? *Journal of Human Kinetics*, 47(1),

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

123–134.

- Mero, A., & Komi, P. V. (1986). Force-time characteristics and running velocity of male sprinters during the acceleration phase of sprinting. *Research Quarterly for Exercise and Sport*, 57(2), 94–98.
- Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2015). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, 112(11), 3921–3930.
- Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, 43(9), 1680–1688.
- Morin, J. B., Petrakos, G., Jiménez-Reyes, P., & Samozino, P. (2017). Sled-pushing versus traditional resistance training for improving horizontal force production in sprint acceleration. *International Journal of Sports Physiology and Performance*, 12(8), 1047–1053.
- Morin, J. B., Samozino, P., Bonnefoy, R., Edouard, P., & Belli, A. (2010). A simple method for measuring horizontal force-velocity-power profile in sprinting. *Journal of Biomechanics*, 43(16), 3113–3117.
- Nagahara, R., Morin, J. B., & Kido, M. (2018). Impulse during sprint acceleration is related to running velocity. *Journal of Biomechanics*, 71, 231–236.
- Rabita, G., Dorel, S., Slawinski, J., Sàez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J. B. (2015). Sprint mechanics in world-class athletes: A new insight into the limits of human locomotion. *Scandinavian Journal of Medicine & Science in Sports*, 25(5), 583–594.
- Schache, A. G., Dorn, T. W., Wrigley, T. V., Brown, N. A. T., & Pandy, M. G. (2014). Stretch and activation of the human hamstrings during sprinting. *Journal of Biomechanics*, 47(11), 2647–2653.
- Seitz, L. B., Barrera-Dominguez, F. J., & Haff, G. G. (2014). The relationship between isometric mid-thigh pull force and sprint acceleration in elite rugby players. *Journal of Strength and Conditioning Research*, 28(12), 3402–3410.
- Weyand, P. G., Lin, J. E., & Bundle, M. W. (2014). Sprint performance-duration relationships are set by the fractional duration of foot contact. *Journal of*

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Applied Physiology, 117(11), 1275–1283.

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(5), 1991–1999.