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INVITED COMMENTARY

Assessing Horizontal Force Production in Resisted Sprinting: Computation and Practical Interpretation

Matt R. Cross, Farhan Tinwala, Seth Lenetsky, Scott R. Brown, Matt Brughelli, Jean-Benoit Morin, and Pierre Samozino

The assessment of horizontal force during overground sprinting is increasingly prevalent in practice and research, stemming from advances in technology and access to simplified yet valid field methods. As researchers search out optimal means of targeting the development of horizontal force, there is considerable interest in the effectiveness of external resistance. Increasing attention in research provides more information surrounding the biomechanics of sprinting in general and insight into the potential methods of developing determinant capacities. However, there is a general lack of consensus on the assessment and computation of horizontal force under resistance, which has resulted in a confusing narrative surrounding the practical applicability of loading parameters for performance enhancement. As such, the aim of this commentary was twofold: to provide a clear narrative of the assessment and computation of horizontal force in resisted sprinting and to clarify and discuss the impact of methodological approaches to subsequent training implementation. Horizontal force computation during resisted sleds, a common sprint-training apparatus in the field, is used as a test case to illustrate the risks associated with substandard methodological practices and improperly accounting for the effects of friction. A practical and operational synthesis is provided to help guide researchers and practitioners in selecting appropriate resistance methods. Finally, an outline of future challenges is presented to aid the development of these approaches.

Keywords: sprint training, heavy sled, system mass, friction coefficient, kinetics, ground-reaction force, power

A key physical determinant of many sports is the ability to express force at a range of movement velocities.[1,2] In sprinting acceleration, assessing the component of ground-reaction force applied in the direction of the sprint (ie, horizontal force [F_h]) can help further our understanding of performance. As such, there is considerable interest in assessing F_h,[3] with applications in monitoring and rehabilitation,[4] as well as the selection of training parameters.[5]

One area of interest is assessing F_h while sprinting against resistance to better understand the kinetic impact of potential training regimes. Unfortunately, measuring F_h during resisted sprinting (eg, towing a sled or using a winch device) is somewhat complex, and ensuring accurate and consistent measurement and computation is crucial. The aim for this commentary is to provide a clear narrative of the assessment and computation of horizontal force in resisted sprinting, and to critically discuss the impact of methodological approach on training applicability.

Interplay of Mechanics During Sprinting Acceleration

During sprinting acceleration, the force produced by muscle aims to overcome inertia and any friction forces. The greater the force (in this case F_h) expressed, the greater the acceleration for a given system mass (body mass plus any additional load; see Table 1). Any external resisting forces impede acceleration for a given F_h output and must be overcome if the athlete is to accelerate. In a typical sprint, no resistive forces are present except air friction force (F_{aero}), which increases with the square of velocity (ie, high at the end of the acceleration phase).[3] In resisted sprinting, both inertia and resistive force can be manipulated.

In a resisted sprint, the same principles can be applied in the horizontal direction as unresisted sprinting.[6] The main differences are that (1) system inertia typically increases (eg, resisted sleds) and, with it, the force required to accelerate, and (2) additional resistive forces are present—the magnitude and manner of which are method dependent (commonly sliding friction force); practically, the result is less acceleration and a lower peak velocity attained per unit of F_h. However, while system inertia is simple, computing resistive force is more complex.

Measurement and Computation of Horizontal Force

Measurement techniques fall into two categories: direct and indirect. The former involves the direct assessment of ground reaction forces using force platforms embedded under the running surface (typically in the ground[7] or under a treadmill belt[8]). From this point, F_h can be separated from the resultant ground reaction force vector. F_h can also be indirectly estimated using a strain gauge attached between the athlete and a fixed point, or resistive device.[9] In this case, the raw output is an "offset force," which makes it difficult to precisely estimate F_h specific to ground contact (a limitation of various force treadmills[3]). Other indirect methods estimate net F_h production over time by utilizing an inverse dynamic approach applied to the center of mass.[6] The approach requires only velocity

Cross and Samozino are with the Interuniversity Laboratory of Biology of Motricity, Savoie Mont Blanc University, Chambéry, France. Cross is with the Scientific and Sports Dept, Fédération Française de Ski, Annecy, France. Cross, Tinwala, Lenetsky, Brown, Brughelli, and Morin are with the Sports Performance Research Inst New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand. Brown is with Neuromuscular and Rehabilitation Robotics Laboratory (NeuRRo Lab), Dept of Physical Medicine and Rehabilitation, University of Michigan Medical School, Ann Arbor, MI. Morin is with the Côte d'Azur University, LAMHESS, Nice, France. Cross (matthew.cross@univ-savoie.net) is corresponding author.

Table 1 Nomenclature, Basic Definitions, Measurement, and Computational Background of Horizontal Force

Definition		Measurement and calculation
F_h	Portion of the ground-reaction force acting in the sprint direction	Measured directly at the point of application using force platforms. Otherwise, estimated as the product of its determinant variables.
a_h	Acceleration occurring in the direction of the sprint	Determined as rate of change in velocity with respect to time. Can be measured via a wide variety of technologies to various degrees of accuracy.
m	Total system mass	Measured using a simple summation of all mass included in the system being accelerated (eg, body mass, vest, loaded sled).
F_{aero}	Aerodynamic friction force	Estimated using published equations, from a combination of athlete characteristics (mass and height, converted to frontal area), environmental characteristics (temperature, wind speed, and pressure), and instantaneous velocity.
F_f	Friction force	Estimated using experimentation or published equations. Magnitude is determined by the application of braking or loading, converted to effective resistance using a coefficient of friction. The coefficient may not be consistent and can change based on loading and/or velocity. Final value may require correction for angle of pulling (which itself can be measured directly or estimated from standing height and tether length).

Base computation: $F_h = m \cdot a_h + F_{aero} + F_f$.

or distance–time measurements and has been used on data from a variety of devices (eg, global positioning systems,[10] radar, laser, photovoltaic cells,[6] and high-speed cameras[11]).

While the former direct approach can provide insight into the specific events occurring, the advantage of the latter indirect approach is that it can more easily be integrated into the field. The effects of resistance on F_h can certainly be measured using direct approaches (typically treadmills[12] or single foot strikes overground[13]), but it is for reasons of practicality that indirect approaches have attracted interest.

Methods of Manipulating F_h Using Resistance in Sprinting

There are four main methods of providing horizontal resistance to an athlete: aerodynamic (eg, parachutes), motorized (otherwise termed "robotic;" eg, 1080 Sprint; 1080 Motion, Austin, TX), pulley (eg, Exergenie, Thousand Oaks, CA), and sliding (eg, sleds or equivalent). While not well examined, aerodynamic resistance should adhere to the same drag computations published on the human body (ie, F_{aero}; permitted shape and drag factor are known). Contemporary motorized devices provide resistance via measured increments of torque via a servo motor.[14] Force production will typically be computed as a product of simulated inertia, resistive value of braking, and acceleration via rotary encoder. Pulley devices provide resistance in the form of friction applied to a drum or directly to a cable in more simple devices, and do not substantially increase the inertia of the system. However, the magnitude and consistency of resistance provided per increment of braking must be experimentally determined. Sliding devices move with the athlete, and consequently increase system inertia. Additional resistive force is also present from the sliding of the device over the ground (ie, friction force [F_f]).

In its simplest form, F_f can be estimated using a basic conversion factor ("coefficient of friction;" μ_k); determined experimentally means approximated based on known values (eg, normative data on the coefficient between metal and grass). μ_k represents the conversion between the normal force the sled load applies to the ground (ie, the sled + additional load under gravity) and the resulting horizontal F_f applied to the athlete. For example, if sled sprinting with a sled mass of 40 kg and a μ_k of 0.3, F_f would be approximately ~128 N. μ_k can change depending on the surface device characteristics, magnitude of normal loading, environmental characteristics, and even movement velocity.[15] One can estimate μ_k using a common handheld "baggage" scale to directly measure the friction force across a range of masses by pulling at a constant speed (fitting a linear regression between pulling force and normal force);[16] however, substantially more complex methods might be necessary to provide accurate results.[17] Interested parties are encouraged to read further.

At present, resisted sleds are probably the most commonly used external horizontal overload,[17,18] and for this reason (and their relative computational complexity), we will use this method to focus the following discussion.

Problems Arising From Inaccurate Computation

A clear problem in the literature is a lack of narrative regarding the type and magnitude of resistive forces (generally, friction) provided by resistance modalities and, consequently, how this is factored into computations of total output. Notably, a recent meta-analysis[19] even classified loading solely on the additional normal load (% body mass), and while surface "types" were reported (eg, "rigid"), this rudimental categorization does not displace or accurately represent friction characteristics. The overarching problem is that, for a given load, the resistance experienced by the athlete could change substantially (eg, doubled or halved[16,17,20,21]) purely as a product of friction characteristics.

To illustrate the problem with a lack of consensus of approach, we will compare methods of two studies[20,22] that determined indirect, external F_h using resisted sleds. Both studies aimed to compute the optimal loading for maximizing horizontal power, and were published in quick succession, but provided markedly different results and conclusions. The first is a study by Cross et al[22] in which F_h was computed at peak velocity (an approach justified[5] and discussed at length[14]) following a friction experiment.[17] The second is a study by Monte et al,[20] who computed F_h throughout the acceleration phase of each sprint while noting kinematic markers.

The base computations (per unresisted sprinting) used in both studies are identical, but they differ in accounting for resistance due to external loading. Cross et al[22] computed F_h by increasing the total inertia of the system per the mass of the sled and harness, and including F_f as a constant (per F_{aero}). F_f was computed using a sled load and an experimentally confirmed μ_k, which varied based on velocity (via a polynomial fit).[17] The angle between the ground and tether was also calculated to help separate the horizontal ground reaction force component from any vertical occurring. Monte et al[20] did not directly compute friction force, but considered the additional resistance as an equivalent load experienced by the athlete. To "correct" for the effects of friction, the initial prescription of each sled mass was reduced by the magnitude of friction–equivalent loading using an experimentally determined μ_k of 0.2 (eg, original mass = 10 kg, equivalent loading = 2 kg, final mass prescribed = 8 kg). In this manner, it appears that the authors believed that the effects of friction force were completely accounted for, although it remains unclear if the reduced or original load was used in F_h computations. Clearly, correcting for "horizontal loading" by subtracting its raw magnitude from that applied vertically is problematic, since F_f is a product of the total normal load of the sled and environmental characteristics (eg, ~1.6-kg-equivalent loading is still experienced for a "corrected" 8-kg sled mass).

The method presented by Monte et al[20] may result in substantial inaccuracies in the force produced to overcome inertia during acceleration (considered mass may differ from that experienced) and an underestimation of friction forces (notably in late sprint phases). To facilitate understanding, Figure 1 displays the effects of this method on computed F_h during sprinting acceleration with two loads. Notably, the limitations of this method are perhaps most apparent in conditions nearing zero acceleration (eg, peak or maintained velocity), since the force to overcome sled friction is "corrected" for in an artificial inertia. Consequently, the computation assumes at constant velocity the only net F_h being produced is to overcome F_{aero}. To emphasize, regardless of whether the sled load is 5 kg or 100 kg, the force produced by the athlete during constant velocity is assumed to be only due to air.

Implications for Training

The F_h output during resisted sprinting is regularly presented as a means of understanding the value of potential training parameters[18,23]; the examples earlier illustrate how methodological problems can directly affect the results on which such judgments are made. Similarly, the methods through which mechanical parameters are measured and computed need to be associated with a clear narrative around their specific applicability.

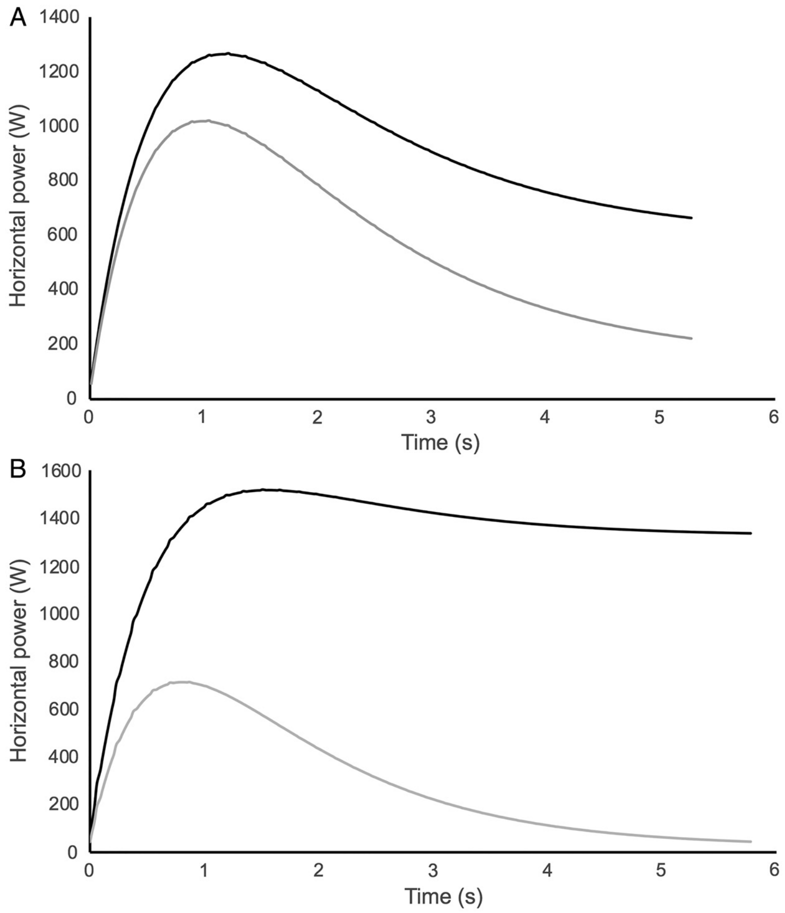

Figure 1 — Illustration of the differences in external maximal power in the horizontal direction over the course of 2 sprints, with (black line) and without (gray line) accounting for the constant variable of friction force, applied to the instantaneous velocity–time data of athletes sprinting with 2 different loading protocols: (A) 20% body-mass load (chosen to be representative of the highest loading protocol used by Monte et al[20]) and (B) 79% body-mass load (corresponding to approximately the mean load maximizing power in Cross et al[22]). Black line indicates computation accounting for the effects of friction force as a constant[17]; gray line, correction computation used by Monte et al.[20] Both examples are based on the same calculation of inertia, on a Mondo track surface, coefficient of friction = ~0.4.

Commonly, measurement occurs under a selection of external protocols, after which instantaneous or average F_h outputs are compared with gain insight into which parameters acutely enhance output (eg, maximizes force or power). However, the nature of such measurement and computation may be problematic for those expecting beneficial training outcomes. As an example, if training resistance is selected based on instantaneous maximization during acceleration,[20] an athlete will similarly spend only a single instant in these "targeted conditions" per acceleration performed. The minimal cumulated time spent in targeted conditions per training block might limit practical benefit and could partially explain the typically similar adaptations experienced in resisted versus unresisted sprinting interventions.[18]

A clear solution to increasing exposure is to find the load that allows targeted conditions to be reached at the peak velocity plateau, since this is the only velocity that can be maintained over several seconds of maximal exercise (fatigue permitting).[5,14,17,22] The interest in this approach is that if resistance is selected to target the development of a given level of F_h at peak velocity, the athlete can spend an extended period (eg, 3–5 s per sprint) near these optimized conditions by simply attaining and maintaining peak velocity. The practical consequence is greater time spent in targeted conditions than other approaches (see Figure 2 for an example of targeting maximum power). Nevertheless, the method has limitations; namely, it ignores the work performed (and fatigue induced) between the start and reaching peak velocity. An alternative approach might be the assessment of loading parameters based on the average output over a distinct period (eg, 10 m). Certainly, this is a valuable avenue for future investigation.

Distinct bands of velocity can be targeted by fixing a specific training load, and these conditions are likely relevant to unloaded sprinting.[5] While some may argue that loading selected in this manner ignores technical specificity because it aims to recreate the conditions experienced during a specific moment of the acceleration phase, it follows that kinematic conditions might be similar when compared in this manner (eg, the instant of 5 $m \cdot s^{-1}$ during acceleration vs 5 $m \cdot s^{-1}$ peak resisted velocity). These similarities (or indeed dissimilarities) require clarification, but do not necessarily degrade the possibility of longitudinal improvement in determinant physical capabilities as part of a balanced periodization. Nevertheless, the actual effects of training using stimuli selected for its kinetic specificity remain unclear,[14] and more research is needed.

Practical Synthesis

We encourage researchers to utilize the measurement of F_h during resisted sprinting but to carefully consider the impact of study design and computation on their conclusions. Where possible,

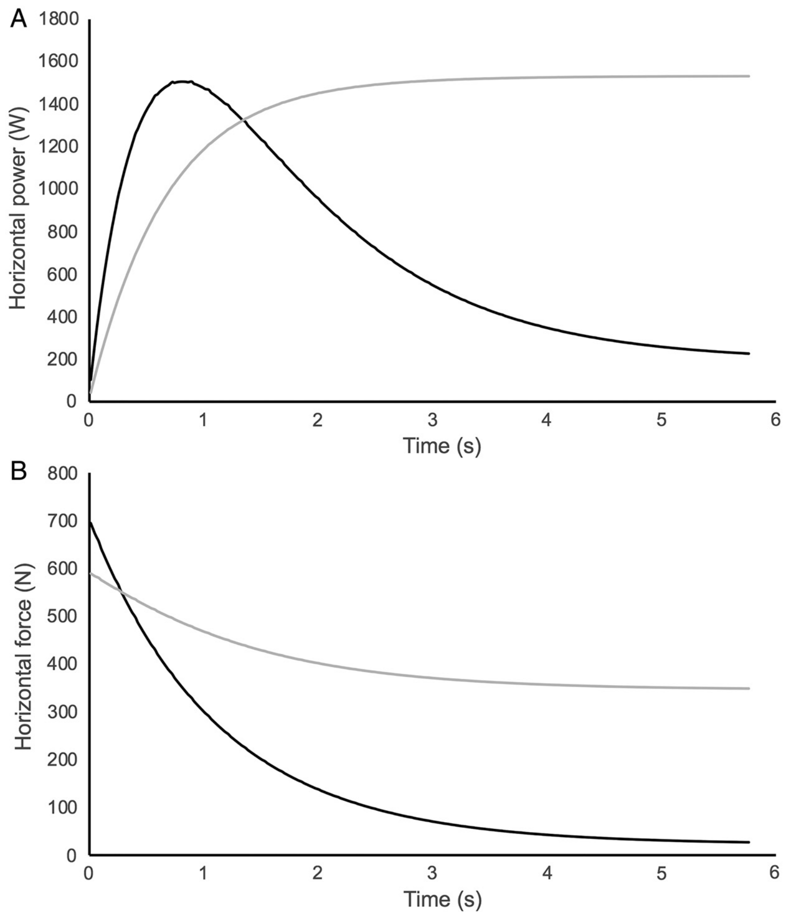

Figure 2 — Graphic showing the differences in (A) power output and (B) F_h over the course of 2 different loading protocols: unloaded sprinting (black line) and 79% body-mass load (gray line). The computation of force for the resisted sprint follows the procedures described in detail elsewhere.[17] This is intended to exemplify the difference in time spent at a targeted kinetic output (in this example, maximum horizontal power), when assessed at maximum resisted velocity compared with during the acceleration phase.

experimentally determine friction coefficients, or consider using an "outcome" variable (eg, decrement in maximum velocity), to select and classify loading parameters. Practitioners may use published coefficients to estimate outputs, while acknowledging substantial errors may occur. Those wishing to use resisted sprinting to target the development of distinct bands output might forgo F_h assessment and simply select loading based on velocity decrement.[5,14,18] Where training implications are valued as an outcome, researchers are encouraged to carefully orient their study design and analysis to maximize applicability to practice, or at least clearly discuss limitations. Finally, the measurement and improvement of F_h does not supplant a balanced approach to improving sprinting performance and, therefore, should not be presented nor interpreted as such by researchers and readers alike.

Conclusions

Rapidly developing technology has made F_h assessment feasible for many practitioners. Assessing F_h can provide valuable insight into athlete capabilities, and can guide training when combined with resisted sprinting. This progress is accompanied with a need for careful implementation and computations. As such, researchers must be attentive in their methodological proceedings and well consider the practical applicability of their findings.

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