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MAXIMIZING LEGGED ACCELERATIONS:

A MATTER OF FORCE, TIME, AND GRAVITY

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MAXIMIZING LEGGED ACCELERATIONS:
A MATTER OF FORCE, TIME, AND GRAVITY

A Dissertation Presented to the Graduate Faculty of the
Annette Caldwell Simmons School of Education and Human Development
Southern Methodist University
in
Partial Fulfillment of the Requirements
for the degree of
Doctor of Philosophy
with a
Major in Applied Physiology
by
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August 06, 2024
ACKNOWLEDGEMENTS

Dr. Peter Weyand, you transformed me from a jock to a scholar. Your guidance has nurtured my potential holistically. In every challenging phase, your advocacy and wisdom have been my guiding stars. You reshaped my passion for sports science into broader academic pursuits.

To Kellie, the love of my life and steadfast partner, your presence has been a sanctuary during the academic storm. Your unwavering support and love have been the quiet, yet powerful force behind every word written in this dissertation. I am endlessly excited for the life and adventures that await us.

Dr. Anthony Petrosino, your support during my final summer of research was crucial to completing this project. Thank you for advocating for me and ensuring I had the resources needed to succeed.

Dr. Eric Bing, thank you for being a pillar of support and wisdom, stepping in as co-chair during a crucial phase. Your mentorship since my undergraduate days has profoundly impacted my scholarly and personal development, inspiring me to strive for excellence.

To my committee members, I am profoundly grateful for your invaluable expertise, constructive feedback, and support throughout this process. Your insights have been crucial in shaping this work.

To my parents, you are the unsung heroes of this journey. Your love, sacrifices, and unyielding support have been the cornerstones of my achievements. This dissertation is as much a result of your guidance as it is of my efforts. Your belief in me has been a constant source of strength, and I owe every success to you.
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Introduction

Locomotor performance limits have long been a source of fascination. The topic has long been a focal point for general curiosity and has broad scientific relevance to the evolution, design, and function of the musculoskeletal system, and has broad applications that spans many contemporary scientific and professional field such as mechanics, robotics, rehabilitation, and athletic performance.

Maximal sprint accelerations are an important locomotor function, but are also complex mechanically and, therefore, not well understood. Perhaps the most promising approach to advancing the understanding of rapid legged acceleration at the whole-body level is the foundation provided by Newton. Newton's laws explain that an object stays in uniform motion unless acted upon by an external force, force equals mass times acceleration, and every action has an equal and opposite reaction. These principles form the basis of our understanding of movement.

The primary forces in human locomotion are those generated between our feet and the ground. Despite the insight provided by Newtonian physics, how the dynamics of foot-ground interactions enable rapid acceleration has not been fully elucidated. While the basic physics of force and bodily motion are fully clear, the integration of musculoskeletal force production, gait mechanics, and bodily motion with external force production is complex.

The long-standing view on rapid legged accelerations is that maximizing sprint acceleration performance requires maximum force (Furusawa et al., 1997; Harland & Steele, 1997; Mero et al., 1983; Morin et al., 2015; Samozino, Rabita, Dorel, Slawinski, Peyrot, Saez de Villarreal, et al., 2016). It is well established that higher forces lead to greater performance in
top-speed sprinting (Furusawa et al., 1997; Weyand et al., 2000). However, the mechanics of sprint acceleration differ significantly, as the forces are considerably lower and the gait mechanics more complex. Therefore an approach that integrates force production, gait, and motion is necessary for understanding and enhancing acceleration performance (Clark & Weyand, 2015).

At the most basic mechanical level, legged acceleration requires runners to satisfy three fundamental kinetic requirements: supporting body weight by pushing downward, accelerating horizontally by pushing backward, and aligning the direction of the push with the body's mass center to avoid rotational instability and pitching about the center of mass (S. B. Williams et al., 2009). The first requirement, supporting body weight, is dictated by gravity and remains relatively constant across steps (Cavagna et al., 1977). The second and third requirements are likely tightly coupled, at least for bipedal runners, as greater horizontal force magnitudes necessitate more acute push angles and precise alignment of the body's center of mass for balance and stability (Kugler & Janshen, 2010). My dissertation explores how runners integrate the three basic requirements to optimize performance and maximize legged accelerations.

My first investigation explores the mechanical constraints on maximal sprint acceleration imposed by the earth’s gravity for both bipedal and quadrupedal runners. Although the fastest quadrupeds exhibit superior acceleration capabilities, both humans and quadrupeds are theoretically subject to the same mechanical constraints, limiting acceleration to 1 G due to gravitational demands. However, common experience suggests that these shared mechanical requirements do not result in equivalent performance capabilities—we all know how easily dogs outpace us when chasing a thrown ball. This study poses a fundamental question: Does the shared mechanical need for both bipedal and quadrupedal runners result in a common
performance limit, or does having two pairs of limbs enable gait mechanics that elevate force in the F=ma equation? If so, how?

The second study, "Optimal Sprint Running Accelerations from Submaximal Push-Off Forces?" examines whether the mechanical demands of sprinting constrain the forces runners apply to avoid dead time in the air and step more frequently. By comparing forces applied during sprint accelerations to those during maximal-effort single-shot dives from sprint start positions onto a landing mat, this research evaluates how each condition influences force application and acceleration.

The third study investigates the impact of different block starting positions on sprint performance. It aims to understand why competitive sprinters prefer staggered-stance block starting positions and examines the effects of block spacing on acceleration and performance. This study tests the hypothesis that prolonging block push-off time via stance elongation decreases the aerial "dead time" before the first step and enables body and limb positions that enhance acceleration on subsequent steps. By evaluating how different starting positions influence push-off time, push angle, push force, and subsequent step acceleration, the findings are expected to provide insights into optimizing start techniques in competitive sprinting.

The questions addressed in my three papers have the potential to advance the basic understanding of the biomechanics of all-out legged accelerations and potentially provide practical applications across several applied fields from engineering to medicine and sports performance.
References


From humans to hounds:
gravity and balance limit sprint running acceleration

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Key words: Running Performance, Ground force application, Dynamic balance, Comparative biomechanics, Greyhounds
Abstract

Sprint running accelerations require runners to apply surface forces that: support body weight by pushing downward, accelerate the body horizontally by pushing backward, and align the direction of the push with the body’s mass center to maintain balance and posture, which imposes an upper limit on the average forward acceleration force equal to the average gravitational force (1.0 G) acting on the runner. This expectation arises from the mechanical constraints imposed by the need to generate sufficient vertical force to support body weight against gravity while simultaneously producing horizontal force to accelerate forward and aligning the push through the center of mass for balance. We tested the 1.0 G hypothesis by acquiring single-second sprint-start data from humans and canine sprinters in competition or equivalent (n=4 each). Additionally, we evaluated single-push data from human sprinters using force-instrumented (n=28) or platform-mounted (n=25) starting blocks against a condition-specific, single-push theorized limit of 1.25 G. The overall single-second race-start acceleration means of the human and canine sprint group (6.79±0.87 m•s⁻², n=8) were significantly less than the theorized maximum of 9.81 m•s⁻². Quadrupeds demonstrated a higher mean acceleration compared to bipeds (7.4±0.39 vs. 6.16±0.39 m•s⁻²). The single-push, mass-specific horizontal force maximums measured for human sprint athletes (0.99±0.06 G) also did not exceed the theorized gravitational limit. These results support our hypothesis that sprint acceleration maximums are imposed by gravitational forces and indicate that quadrupeds operate closer to this earthly limit than bipeds.
**Introduction**

The maximal sprint accelerations of humans are considerably less rapid than those of the swiftest quadrupedal runners. Even the greatest recorded increases in speed per unit time for humans in competition (Best & Partridge, 1929; Brüggemann et al., 1999) are only roughly half of those observed for cheetahs and greyhounds accelerating from standing starts (Gómez et al., 2013; Hudson et al., 2012; Rabita et al., 2015). The ability of these swift feline and canine athletes to attain speeds of 18 to 29 meters per second within 50 meters or less from a standing start (Hudson et al., 2012; Sharp, 1997) would allow them to complete a 100-meter dash in just over half the time required for the fastest human athletes.

Muscle fiber adaptations for speed and power have long provided a scientifically attractive explanation (Hill, 1927) for the superior running performances of these quadrupedal athletes. However, measurements of the mechanical (West et al., 2013) and metabolic properties (Dobson et al., 1988; T. M. Williams et al., 1997) of their skeletal muscles reveal surprisingly limited adaptations for speed. Thus, sprint performance differences between humans and quadrupedal runners do not appear to be explained at the cellular and tissue levels. Here, we consider the alternative possibility that having only two limbs limits the acceleration performance of human runners. Two gait factors seem likely to impose mechanical limits for bipedal vs. quadrupedal runners. Two-legged runners: 1) can only apply ground force with one limb at a time when running, and 2) require significant aerial periods between steps during which acceleration cannot occur.

However, two and four-legged runners are subject to common mechanical constraints when accelerating in the earth’s gravitational field. They must apply sufficient foot-ground forces to support the body’s weight against gravity (vertical component) while simultaneously
pushing backward against the surface (horizontal component) to increase the body’s forward velocity. They also need to align the direction of each push on the ground with their body’s center of mass to avoid rotation or a “pitching” of the body and a potential loss of balance (Mann, 2018; S. B. Williams et al., 2009) The lower push angles often advocated for sprint acceleration performance (Morin et al., 2011; Samozino, Rabita, Dorel, Slawinski, Peyrot, Saez De Villarreal, et al., 2016) could theoretically increase the horizontal component of the ground reaction force and thereby increase the body’s horizontal acceleration. However, very low angles will inevitably introduce misalignment between the orientation of the total ground reaction force and the body’s center of mass. The turning forces that result from misalignment introduce backward bodily rotation or pitching. This phenomenon is commonly observed during motorcycle “wheelies” (S. B. Williams et al., 2009) when large, rear-wheel propulsive forces result in low push angles and an upward rotation of the motorcycle and rider.

The data available suggest that simultaneously satisfying balance and gravitational support force requirements constrains the minimum push angle for both human and quadrupedal runners to an approximate minimum of 45° during maximal sprint accelerations (Mann, 2018; Rabita et al., 2015; Walter & Carrier, 2009). An observed minimum at an angle of 45° at which the horizontal and vertical components of the ground force are equal identifies a convenient, approximate theoretical maximum for horizontal acceleration of 1.0 G or 9.8 m·s⁻². Runners pushing with average horizontal forces greater than body weight as needed for acceleration to exceed 1.0 G, risk two negative performance outcomes. First, if a horizontal force > 1.0 G is accomplished with a low push angle, an undesirable backward rotation or pitching of the body will result. Second, a push oriented at or near a 45° angle with horizontal and vertical components substantially exceeding 1.0 body weight, will elevate the body’s center of mass and
thereby introduce a prolonged subsequent aerial period. Prolonged aerial times compromise acceleration by delaying the initiation of the subsequent step and push on the ground. Thus, existing constraints in the earth’s gravitational field identify a theoretical mechanical maximum for the rate at which velocity can increase during sprint running: 9.8 m s$^{-2}$ during each second a runner pushes on the ground.

Here, we examined the acceleration performance limits of human runners in two steps. First, we considered how human runners simultaneously satisfy the basic mechanical requirements for support, propulsion, and balance during sprint acceleration. Second, we compared the mechanical basis of sprint acceleration and performance in human and quadrupedal runners. Our first hypothesis was that gravitational support force and balance requirements would limit stance-averaged running accelerations to a value approximately equal to gravitational acceleration on earth. Our second hypothesis was that bipedalism limits sprint acceleration performance by requiring aerial periods between steps during which propulsion and acceleration cannot occur.
Methods

Mechanical Requirements of Accelerated Sprint Running

Runners accelerating on level ground must satisfy three kinetic requirements: 1) supporting body weight by pushing downward, 2) accelerating horizontally by pushing backward, and 3) aligning the direction of the push with the body’s mass center to avoid bodily rotation (longitudinal or head-to-toe axis, Figures 1 and 2A) that would impair or prevent running.

The magnitude of the first requirement of supporting body weight is set by the pull of gravity on the body’s mass \( M_b \cdot G = F_{Wb} \) and is therefore relatively constant across steps over time and is not affected by changes in horizontal velocity. The relatively constant vertical force requirement tightly couples the of the second and third requirements to one another as illustrated in Figure 2B. The greater the magnitude of the horizontal force, the more forward oriented the ground reaction force angle, and the more anterior the position of the COM must be to align with push direction for balance and stability (Kugler & Janshen, 2010; Roberts & Scales, 2002). The integration of the three kinetic requirements that accelerating runners must satisfy (Figure 2B) can be expressed as:

\[
F_z = F_y \cdot \tan \theta
\]

where \( F_z \) is vertical ground reaction force, \( F_y \) is the horizontal ground reaction force, \( \tan \) is tangent function, and \( \theta \) is the angle between the running surface and the reaction force vector corresponding to the push of the runner’s limb on the ground.

In practice, maximal accelerations involve push angles with the ground that are typically no less than 45°. This is the case for human sprinters using starting blocks (Mero et al., 1983; Rabita et al., 2015; Slawinski, Bonnefoy, Levêque, et al., 2010; Willwacher et al., 2016) as well as for greyhounds and polo ponies in competition (S. B. Williams et al., 2009). Given a value of
1.0 for the tan function at a minimum push angle of 45° (i.e. horizontal and vertical forces of equal magnitude), the maximum average horizontal force for positive acceleration should be effectively equal to the body’s weight ($F_y = F_{Wb}$ and $F_{y\text{-max}}/F_{Wb} = 1.0$). This maximum assumes that the runner should adopt a largely horizontal center of mass trajectory to avoid time in the air when force application and acceleration cannot occur. These conditions limit the maximum sprint acceleration to a value equal to the force of the gravitational field in which the runner is accelerating. Thus, on earth, the sprint acceleration maximum can be expressed as:

$$A_{y\text{-max}} = F_{y\text{-max}}/F_{Wb} \cdot G = 9.8 \text{ m} \cdot \text{s}^{-2}$$

(2)

where $A_{y\text{-max}}$ is maximum horizontal acceleration, $F_{y\text{-max}}$ is the maximum horizontal ground reaction force, $F_{Wb}$ is the weight of the body, and $G$ is acceleration due to gravity. This theoretical maximum should be regarded as an approximate upper limit for the time- or step-averaged acceleration observed across the initial portion of a maximal, level-ground effort from a standstill. Since the instantaneous horizontal forces applied could exceed the body’s weight transiently, the limit should be regarded as an approximate step-averaged maximum over the brief initial portion of a sprint.

An illustrated example of our theoretical maximum as a time-average value from a bipedal runner that includes both the contact periods during which ground force is applied and the aerial periods between-steps when it is not, is provided in Figure 3. Representative velocities, accelerations and horizontal forces appear as per step averages for a competitive human sprinter at the outset of an all-out sprint in Figure 3 (Rabita et al., 2015). Per panels 3A and B, on a time-averaged basis over the first full second of the effort, the magnitude of the horizontal forces the runner applied and his center of mass acceleration both fall below the theorized limits of $F_{y\text{-max}}/F_{Wb} \leq 1.0$ and $A_{y\text{-max}} \leq 1.0 \text{ G}$.
**Single-Push Limits:** The considerations for step-average limits rely on an assumption that the height of the body’s center of mass does not change over time. While this assumption holds under most level ground sprint running circumstances, it is not fully valid for human athletes using starting blocks at the outset of a competitive sprint event. The four-point, starting position sprinters typically assume, with both arms and legs contacting the surface for the desired support, stability and limb & body positions, places the center of mass closer to the ground than during upright running. Consequently, competitive sprint starts from blocks introduce a requirement to elevate the body’s center of mass. Also introduced is a secondary requirement to rotate the body slightly to attain a more upright running position. Because the extent of the rotational requirement is limited and occurs gradually, the angular accelerations required along the body’s longitudinal axis are relatively low (Nagahara et al., 2014; Slawinski, Bonnefoy, Levêque, et al., 2010). Consequently, rotational motion effects on the angle of ground force application needed for balance and the maintenance of a running posture are minimal. In contrast, the center of mass elevations observed introduce force requirements sufficiently large to warrant inclusion into theorized maximums for this condition.

The quality of existing kinetic and kinematic data from sprint starts should enable the additional force requirement of block starts to be determined. The center of mass elevation during the starting push from the blocks is generally reported to be 0.15 m (Mero et al., 1983; Nagahara et al., 2014; Slawinski, Bonnefoy, Levêque, et al., 2010). If a push angle of 45° and duration of 0.35 s (Mero et al., 1983; Rabita et al., 2015; Willwacher et al., 2016) are utilized, the average vertical force required above the body’s weight during the push $\approx 0.25 \times F_{Wb}$. This follows from an average vertical velocity during the block push of 0.42 m/s need for an elevation of 0.15 m to occur in 0.35 s ($\Delta h = 0.15 \text{ m}/0.35 \text{ s}$). Assuming constant vertical acceleration
during the push, the final vertical velocity would be twice the average velocity, and therefore
0.84 m/s (2.0 • 0.42 m/s), and the average vertical acceleration would be 2.40 m·s⁻² (0.84 m·s⁻²
/0.35 s). These circumstances correspond to a push-averaged mass-specific force of 0.25 times
the body’s weight [(M_b•2.40 m·s⁻²)/(M_b•9.81 m·s⁻²)) = 0.25_wb] and a corresponding theoretical
horizontal force maximum for block starts of F_{y-max}/F_{Wb} = 1.25:

$$A_{y-max} = F_{y-max}/F_{Wb} \cdot G = 1.25 \cdot 9.8 \text{ m·s}^{-2} = 12.2 \text{ m·s}^{-2}$$  \hspace{1cm} (3)

where 12.2 m·s⁻² represents a theoretical push-averaged maximum acceleration limit for human
sprinters exiting starting blocks.

*Experimental Design*

We tested three maximal acceleration hypotheses using data acquired from the literature,
laboratory and field. Literature data on the fastest bipedal and quadrupedal sprint runners for
whom data was available were used to evaluate whether their step-averaged maximal
accelerations over the initial second of an all-out sprint exceeded our theorized limit equal to the
rate of gravitational acceleration on earth. Subsequently, we tested whether the maximal
accelerations of the quadrupedal runners exceeded those of the bipedal runners. Third, using
original field and laboratory data acquired from competitive human sprinters, we tested our
theorized, condition-specific, single push-average limit from blocks of 1.25 G.

Per our theoretical framework, we predicted that: 1) the mean accelerations of the
athletics dogs and humans combined would be less than our step-averaged theorized limit of 1.0
G or 9.81 m·s⁻² during the first second of their all-out sprints, 2) the maximal accelerations of the
quadrupeds would exceed those of the bipeds, and 3) the human sprint athletes starting from
blocks would have single-push accelerations equal to or below our push-averaged theoretical maximum of 1.25 G or 12.2 m·s⁻².

*Step-Averaged Data Acquisition*

Greyhounds: Velocity vs. time data for three greyhound literature curves were acquired by digitizing data (*WebPlotDigitizer - Extract Data from Plots, Images, and Maps.*) from Hossain et al., 2019 and Eager et al., 2021 acquired with a real-time location system (RTLS, IsoLynx) utilizing wireless tracking tags integrated into each dog’s racing gear and smart nodes to capture instantaneous two-dimensional position with an accuracy of ± 15 cm. Position data were acquired 30 times per second from a series of signal towers positioned above the racetrack along its outside perimeter (Eager et al., 2021). The first 0.2 seconds of race data were not included because the starting cage metal interfered with signal reception. The velocity-time data for two dogs from Hossain et al. (Figure 5, 2019) were then derived to determine the greyhounds' acceleration. A third velocity vs. time curve for the mean curve for eight greyhounds reported in Eager et al. (Figure 9, 2021) was also digitized.

Labrador Retriever: Center of mass acceleration, velocity and position for one Labrador retriever were determined from the ground reaction force data reported by Walter & Carrier (Figure 7, 2009; Dog A, 33.1 kg). Vertical and horizontal ground reaction force data were acquired for the first three hindlimb and two forelimb contacts from Dog A using a single Kistler 9281B 40 by 60 cm force platform recording at 500 Hz. Mean data from multiple trials from different starting positions as needed to capture footfalls on a single force platform were compiled into representative averages for the largely simultaneous contacts of both hindlimbs and separate contacts of the leading and trailing forelimb. The investigators reported achieving maximal
efforts for each trial by having dog A chase an investigator running with a hot dog or a thrown tennis ball. Trials deemed submaximal based on performance, perception of effort and/or fatigue were discarded.

Human Sprinters: Position vs. time data: Position vs. time data were acquired for three male sprinters and determined kinetically for a fourth. The position vs. time profile of the current male world record holder during the first second of the World Championships 100-meter final in 2009 (as presented in Gómez et al., 2013) and the 1997 World Champion in the World Championship 100-meter final. In both cases, position vs. time data were acquired with a laser measurement system at a minimum frequency of 50 Hz (Graubner & Nixdorf, 2009) and with a reported error of 0.02 s or less in time to complete a given distance. Position and velocity vs. time were determined for a third sprinter who was a runner-up at the European Championships using a custom, wire velocimeter (Witters et al., 1985) during all-out sprints administered at a testing facility (van Coppenolle et al., 1989). This device utilized a thin nylon wire tethered to the athlete and tensioned to approximately 1 N. The position and time data were integrated with microprocessors and validated with high-speed video data. Velocity measurement error was determined to be 0.01% for speeds up to 15 meters per second. The data for each of the human sprint athletes were digitized from the sources identified also using WebPlotDigitizer 4.5.

For one male sprinter (73.3 kg, 100-meter personal best =10.4 s), ground reaction force data from the initial steps of an all-out sprint across force platforms (Figure 1 of Rabita et al., 2015) were digitized also using WebPlotDigitizer4. The center of mass velocity across the first second of running after a motionless start was determined from the digitized horizontal ground reaction force and body mass.
Push-Averaged Data Acquisition

Force-Platform: Twenty-five track athletes, 19 males (mass=78.4 ± 7.0 kg) and 6 females
(mass=58.4 ± 5.4 kg) between 18 and 40 years of age volunteered and provided written informed
consent [IRB protocol H13-038-2013]. All the athletes were competitive sprint or hurdle
athletes and had extensive experience sprinting from starting blocks. The range of 100-meter
personal bests for the male athletes [mean = 10.45 ± 0.67 s; range from 9.85 to 11.80 seconds].
Six of the males had 100-meter personal best times ≤ 10.00 s. The personal bests of the female
athletes [mean: 11.23 ± 0.36 s; range 10.74 to 11.74 s].

Each athlete completed six 5-meter sprint trials in an indoor laboratory setting that
provided 20 meters of space beyond the starting line and a crash mat affixed to the far wall.
Participants were instructed to perform maximal effort sprints through 5 meters. The athletes
used a standard starting block system (Cantabrian Catapult™) that was modified to enable the
beam to be bolted to the force plates and to allow participants to choose their preferred distance
between each block the starting line. Ground reaction force data were acquired from the first one
or two of three contiguous force platforms (Bertec, Model FP9090-15-4000, 90 x 90 cm). Force
data were captured at 1000 Hz with a National Instruments PCIe-6323 data acquisition board (32
analog inputs, 250 kS/s, 16-bit resolution) using LabVIEW (2011) software. These data were
post-filtered using a lowpass, fourth-order, zero-phase-shift Butterworth filter with a cutoff
frequency of 50 Hz. Prior to each trial, participants were positioned into their blocks, were
provided with the verbal queueing sequence of "Ready... Set..." before initiating the trial at the
time they chose following the "Set" command.

Force-Instrumented Starting Blocks: Force data were acquired from 28 sprint athletes using
custom, force-instrumented starting blocks developed by Willwacher and colleagues
(Willwacher et al, 2016). The data included here are from a subset of the fastest athletes in the
data set previously presented in Willwacher et al (2016). The cohort of 28 athletes was
comprised of 18 males (Mass=78.0 ± 6.3 kg; mean 100-meter PR = 10.21 ± 0.37 s) and 10
females (Mass=63.2 ± 7.4 kg; mean 100-meter PR = 11.31 ± 0.18 s) and included the two fastest
male 100-meter athletes in history.

These blocks consisted of a steel center rail with separate block bases and force sensing
units for each foot, accommodating different inclination angles and placements. Small custom-
made force platforms, each including four piezo-type 3D force transducers from Kistler AG,
Switzerland, were attached to the tops of the block bases for precise force measurements. The
force signals were digitized at a sampling rate of 10,000 Hz and subsequently filtered using a 4th
order digital Butterworth filter with a 120 Hz cut-off frequency. These signals were then
transformed from the local (tilted) starting-block reference system to a global coordinate system
with the x-axis aligned forward along the running surface, the y-axis to the left, and the z-axis
pointing vertically upwards. Each athlete performed a minimum of three full-effort sprint starts
over 20 meters. The best performance of the three attempts was used for further analysis. The
onset of the push was defined as the first instant when the resultant force curves increased above
the baseline force in the set position. Block clearance was defined as the first instant when the
resultant force of the front block dropped below a threshold of 50 N. Each athlete performed a
minimum of three full-effort sprint starts over 20 meters.

Statistics

Our first hypothesis that the initial sprint accelerations of our eight bipedal and quadrupedal
sprint athletes would not exceed 1G was tested using the mean acceleration of these athletes over
the initial second of all-out sprints from a standstill using a one-tailed t-test vs. a fixed null value of 9.8 m·s\(^{-2}\). Our second hypothesis that bipeds would accelerate less quickly than quadrupeds was tested with an unpaired t-test at an alpha level ≤ 0.05. Our third hypothesis that the push-averaged acceleration means of our 53 human athletes starting from starting blocks would be equal to or less than 1.25 G was also tested with a one-tailed t-test against a fixed null value of 12.25 m·s\(^{-2}\).
Results

*Step-Averaged Acceleration Maximums*

Acceleration data from the eight athletic runners for whom we acquired single-second sprint start data appear in Table 1. The single sample t-test conducted to compare the mean all-out acceleration of these eight athletic runners of 6.8±0.9 m·s⁻² to our theoretical maximum value of 9.8 m/s² indicated that this value was significantly lower (p < 0.001) supporting hypothesis 1. The acceleration means of the four bipedal runners appearing in Table 1 were significantly slower than those of the quadrupedal runners (unpaired t-test, p=0.03) supporting hypothesis 2 that the bipedal athletes would not accelerate as rapidly as the quadrupedal runners.

The average horizontal ground reaction forces and velocity vs. time data for three of the quadrupeds (two greyhound curves, one Labrador) and the two fastest human athletes in the sample appear in Figure 4A and B, respectively. The Fy/Wb forces applied, and corresponding acceleration values were greater for the three quadrupedal sprint curves (greyhound 1 - blue, greyhound curve 2 - red and Labrador Retriever curve - purple) than the two bipedal human athletes. Per panel A, the horizontal forces of all five of these sprints, when averaged across the full second, fell well below our theorized maximum acceleration value of 9.8 m·s⁻². When the instantaneous velocities were plotted as a function of time over the 1.0 second interval, the instantaneous accelerations in all five cases were at or very near our hypothesized limit (panel B, dashed line) in the initial portion of sprint, but fell progressively farther below the hypothetical maximum as the sprint progressed beyond the first 0.25 seconds toward the 1.0 second mark.
**Ground Reaction Force-Time Patterns**

The time sequence of ground force application over the initial second of all-out sprinting appears for one bipedal runner and one quadrupedal runner in Figure 5, panels A and B, for the respective runners. For each of the sprint acceleration steps for both runners, the horizontal forces (black lines) for the initial push against the ground at the outset of the sprint are approximately equal to the theorized $F_y$ maximum of 1.0 times the body’s weight and nearly equal to the vertical forces (gray lines). With successive steps the horizontal impulses ($=F_y/W_b\cdot time$) become smaller resulting in progressively smaller per step changes in velocity for both runners. For the human runner, the per step changes in speed become smaller also because the magnitude of the horizontal force also diminishes, most particularly vs. the initial step when the runner is pushing against starting blocks. The acceleration of the human runner is also relatively lower because of the presence of aerial periods between steps when the propulsive forces equal zero as well as small braking forces just after initial contact on steps two, three and four. For the quadrupedal runner, horizontal force application by the forelimbs begins before hindlimb force application has ends. Consequently, the initial-sprint quadrupedal stride cycles do not have aerial periods when force application equal zero. Additionally, negative horizontal or braking forces are not present. Thus, quadrupedal acceleration occurs with a continuous propelling impulse.

**Push-Averaged Block Acceleration Maximums**

Push-averaged horizontal starting block forces as a function of 100-meter personal best times for the 53 athletic sprinters who performed all-out sprints in laboratory and track settings appear in Figure 6. Per the figure, the horizontal forces during the block push-offs of all but one of the 53
athletes fell below the theoretical maximum for this condition of 1.25 G and 12.2 m·s\(^{-2}\).
(p=0.0024). The one sample t-test comparing the mean horizontal block push of the entire group of athletes (\(F_y/W_b = 0.99 \pm 0.11\)) indicated that their mean push-off forces were significantly lower than condition theorized maximum of 1.25 (p<0.001).

The negative slope of the best-fit linear regression indicated that the swifter 100-meter runners had more forceful horizontal block pushes. The means for the athletes starting on the force platform (closed circles) and instrumented starting blocks (closed triangle) were similar in magnitude.

Theory Versus Observation

The mean push angle observed for the 25 athletes starting from force platform-mounted blocks of 49.2\(\pm\)2.4\(^\circ\) was slightly above the theoretical minimum of 45\(^\circ\). None of the original 150 individual laboratory trial observations [25 athletes \(\times\) 6 trials/athlete] utilized a block push-average angle below 45.0\(^\circ\) (range: 45.0 to 55.8\(^\circ\)) with a mean push-averaged \(F_y/W_b\) of 0.99 \(\pm\) 0.11 \(W_b\) and \(F_z/W_b\) of 1.18 \(\pm\) 0.06 \(W_b\), the latter also being in close agreement with the \textit{a priori} theoretical value of 1.25 \(W_b\) for block starts. The magnitude of the push-averaged horizontal force accounted for \(\frac{3}{4}\text{ths}\) of the variation in push angle (\(\theta^\circ = -20.7 \times F_y/W_b + 70.8\), \(R^2 = 0.75\)). The mean aerial time elapsing between block clearance and contact on the ensuing step was 0.061 \(\pm\) 0.029 s.


**Discussion**

Our overall objective was to test the idea that the sprint running acceleration maximums are directly set by the gravitational force acting on the runner. Each of the three tests of this idea we implemented yielded positive results. First, we found that the maximal single-second accelerations at the outset of all-out sprints by eight highly athletic sprinters did not exceed the hypothesized limit (6.8 ± 0.9 vs. 9.8 m·s\(^{-2}\)). Second, we found that having two sets of limbs that increase the relative time ground force application enabled quadrupedal runners to operate closer to the theorized acceleration maximum than bipedal runners (7.4 vs. 6.3 m·s\(^{-2}\)). Third, we found the mean acceleration of a cohort of 53 human athletes that included some of the best sprinters in human history, also did not exceed the gravitational limit when initiating sprints from starting blocks designed to enhance push-off forces and acceleration. Accordingly, we conclude that the balance and force application requirements of running limit sprint accelerations to 9.8 m·s\(^{-2}\) on earth.

*Single-Second Position, Velocity and Acceleration Data: Validity Considerations*

Our single-second acceleration values on sprint athletes were acquired using four different technologies that provided or enabled position and velocity data to be determined on very brief time scales. Several evaluations support the validity of these data for our analytic purposes here. At a general level, the four human velocity-time curves, although acquired with three different techniques, corresponded in a rank ordered fashion to the performance capabilities of these athletes. Similarly, the single-second greyhound velocity-time data, which began just after the dogs cleared their starting gates, was highly reproducible across multiple dogs and races (Figure 7, Eager et al, 2021). The force-motion relationships utilized for the first second of running for
the Labrador retriever and one human sprinter were acquired at 500 and 1,000 Hz respectively and are considered a gold standard technique for determining center of mass motion from mechanical first principles. The data that were likely least accurate were acquired with a laser positioning system for the WR and WC human sprinter at 50 Hz, and an IsoLynx location system for the greyhounds that operated at 30 Hz. The investigators using the respective techniques reported mean, single-data point position errors of 0.10 and 0.15 meters, respectively, for these measurement systems. These errors would alter the mean 1.0 s acceleration values presented for the two human and three greyhound curves by 3.2 and 3.6%, respectively. However, given the data processing routines and accuracy of the best-fit equations used to fit the data streams in these samples, the actual error present was undoubtedly considerably less.

Step-Averaged Sprint Acceleration Limits

The step-averaged acceleration limit postulated here is mathematically equal to that put forward for greyhounds previously by Williams and colleagues (2009), and later suggested to apply to cheetahs by Wilson and colleagues (2013). Williams et al derivation of the greyhound maximum was based on the bodily dimensions of the dogs in conjunction with earth’s gravity. Our more general maximum was based on the minimum ground force application angles deemed possible for both bipedal and quadrupedal runners when sprinting. Our proposed minimum was informed by Williams et al’s results with both greyhounds and polo ponies as well as numerous observations on human sprint athletes (Cavagna et al., 1971; Mero et al., 1983; Rabita et al., 2015; Slawinski, Bonnefoy, Ontanon, et al., 2010; Willwacher et al., 2016). The maximum we formulated, as well as the underlying assumptions were well-supported by our results. When we examined the best data available for the maximal sprint accelerations of human and canine sprint
athletes at the outset of their races, both species accelerated at rates significantly lower than the hypothesized limit, particularly in the latter portion of the single-second interval. Additionally, the first step force application measures we acquired in the lab fully supported our minimal angle assumption.

Given the support from these data specifically acquired here to provide the most rigorous test of the limit, the conformation of the instantaneous accelerations of cheetahs hunting in the wild, the 9.8 m·s\(^{-2}\) to the limit (Figure 4b, Wilson et al., 2013), the much slower maximal, or near-maximal accelerations documented for both larger cursorial quadrupeds (S. B. Williams et al., 2009) and smaller cursorial bipeds (Roberts & Scales, 2002), the conclusion that level-ground, sprint running accelerations on earth, regardless of species, do not exceed a maximum of 9.8 ms\(^{2}\) seems both warranted and conservative.

**Bipedal vs. Quadrupedal Sprint Acceleration Limits**

Based on the timing of ground force application across steps at the outset of all-out sprints from human runners and the more limited data available for dogs (Walter & Carrier, 2009, Figure 7&8), we hypothesized *a priori* that having two sets of limbs would enable superior sprint accelerations in athletic quadrupeds. This was based largely on the inability of bipeds to avoid periods between steps when the ground forces applied were either very limited (Roberts & Scales, 2002) or absent entirely because between-step minimum aerial time was needed for limb repositioning (Colyer et al., 2019; Rabita et al., 2015). The data from both smaller and larger dogs performing all-out sprint accelerations indicated the alternating periods of force application by the fore- and hindlimbs enabled propulsive force application over the initial second of all-out sprint accelerations that was essentially continuous as illustrated for the larger dog in Figure 4.
The consequences of nearly continuous force application by the quadruped in Figure 5B vs. the bipedal runner who had periods of force application that were both zero and briefly negative (Figure 5A) were several. The mean acceleration values of the four quadrupeds in our cohort exceeded those of our highly athletic human sprinters by roughly 20%. These mean differences were present despite the acceleration values in the earliest portion of the sprint efforts being roughly equal (Figure 4B). As would perhaps be expected, the accelerations corresponding to the initial propulsive pushes by both cohorts resulted in similar accelerations over the initial third of the one-second interval. The differences between cohorts over the entire second resulted largely from the velocity changes in the latter half of the period when time-averaged propulsive bipedal force application was reduced by aerial periods not present in the quadrupedal pattern. Consequently, the velocity-time curves of the bipeds and quadrupeds were similar in the early portion of the single-second interval and divergent in the latter portion (Figure 5B). The overall effect of limb number on the sprint accelerations in question is perhaps best highlighted by the velocity of the Labrador retriever chasing a hot dog surpassing that of the fastest human in history in his fastest ever race in the latter portion of the sprint interval we examined.

**Push-Averaged Sprint Acceleration Limits**

One of the most salient questions regarding the sprint acceleration limit formulated and tested here is whether our positive results reflect correct formulation of mechanical limits that are task-specific only, or alternatively, are perhaps both task-specific and representative of musculoskeletal force maximums of the extending limbs. With respect to this question, the block start data acquired from specialized, accomplished human sprinters are uniquely
informative. This is the case because the block start condition, by elevating the vertical force requirement above the body’s weight, similarly elevated the horizontal forces that are theoretically possible at the 45° minimum push angle. If sprint acceleration force application without starting blocks is condition limited and submaximal, the block condition would presumably elevate the horizontal force application to mean values approaching 1.25, or perhaps 1.18 Wb.

The mean $F_y/W_b$ of $0.99 \pm 0.11$ we observed was indeed greater than the one-second means from our one second, multiple-step means, but nonetheless below the condition-specific maximum theorized for the starting block condition. If we reasonably assume high skill levels of the athletes executing this task, the mean result we would have theoretically observed, absent a muscular extensor force limitation would be an $F_y/W_b$ equal to the $F_y/W_b$ value and therefore 1.18 Wb. The acquisition of a measured was 0.99 that was substantially lower implies that these athletes were, on average, operating at both their running-specific mechanical and their limb extensor force limits.

However, the negative slope between best 100-meter performance time and the push-average $F_y/W_b$ values of our sprint athletes (Figure 6) indicates that the superior sprinters did on average operated closer to the theorized $F_y/W_b$ limit for this condition. Indeed, five of our 25 athletes had $F_y/W_b$ values that were within 0.1 Wb of their theorized push-average limit or above. All these athletes had 100-meter personal best times between 9.85-10.60 s. These results leave open the possibility that the swiftest human sprint athletes operate at, or perhaps below, their limb extensor force limits in their initial push out of starting blocks.
Sprint Accelerations in Hyper and Hypo-Gravity

A direct, but non-intuitive result from our theorized sprint acceleration limits and their physical basis is that reducing gravity, and thereby lowering the force requirements of locomotion would impair sprint accelerations, and conversely, that hyper-gravity environments could potentially elevate them. The groundbreaking contributions of Margaria & Cavagna, 1964 in advance of the Apollo lunar missions reached the same conclusion regarding sprint running performance on the moon. And they did so relying largely on the same mechanical logic we have relied upon here. They specifically noted that reduced gravity imposes two sprint acceleration limitations: 1) horizontal force maximums that are reduced in parallel with the gravitational force acting on the runner, and 2) elevated between-step aerial times that prolong the portions of the running stride when force application cannot occur.

Whether the hyper-gravity condition would enhance the push- and step-averaged sprint acceleration limits considered here depends on the critical question raised by the data appearing in Figure 6: do sprint athletes operate at or below their limb force limits at the outset of maximal sprint running efforts?
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https://doi.org/10.1242/jeb.066720


https://doi.org/10.1242/bio.20148284


Author Contributions

LCB: conceptualization, data collection, data analysis, figure preparation, writing, and editing.

SW: data collection and editing.

PGW: conceptualization, data collection, data analysis, writing, and editing.

All authors have reviewed and approved the manuscript and are accountable for its content.

Conflict of Interest

The authors declare no competing interests.

Funding

This research was funded by a Fairess Simmons Doctoral Fellowship to LCB and the Glenn Simmons Endowment to PGW.

Acknowledgments

We extend our gratitude to Kenneth Clark and Laurence Ryan for engaging in early scientific discussions, and to Rae Edwards, Darryl Woodson, and Jon McDowell for their significant help with subject recruitment.
### Table 1. Average Horizontal Velocity, Acceleration, and Force over 1.0 s

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<th>Avg. Acceleration (m·s(^{-2}))</th>
<th>Avg. Force(_y) (W(_b))</th>
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\[ p = 0.03 \]
Figure Captions

**Figure 1.** Schematic representations of alignment and misalignment of the ground reaction force vector with the center of mass of an accelerating runner. Full alignment of the direction of the ground force application and reaction force vector (leftmost image) with the body’s mass center provides the balance and stability about the head-to-toe axis needed to maintain a running posture. More horizontally oriented pushes (center image) result in acute ground reaction force angles and a reaction force vector that passes below the body’s center of mass. This misalignment introduces counterclockwise rotation about the body’s head-to-toe axis, known as a “wheelie effect”. More perpendicular push angles of ground force application (rightmost image) introduce a reaction force vector oriented above the body’s mass center thereby introducing a loss of balance and running stability due to the clockwise rotation of the body.

**Figure 2.** (A) A free body diagram of an accelerating bipedal runner applying ground force at an angle of 45° (A). The direction of the push illustrated results in a resultant ground reaction force (GRF) with equal vertical ($F_{z-avg}$) and horizontal components ($F_{y-avg}$) and therefore oriented at an angle ($\theta_{avg}$) of 45° relative to the ground. The vertical component of the reaction force offsets the pull of gravity on the runner’s body weight ($MG$) while the horizontal component introduces an unbalanced force that results in the forward acceleration of the body’s mass ($MA_{y-vg}$). (B) When the vertical ground reaction force equals the body’s weight ($F_{z-avg} = MG$), the angle of the ground reaction force vector $\theta_{avg}$ is fully determined by the magnitude of the horizontal ground reaction force, $F_{y-avg}$. These relationships introduce theoretical acceleration and horizontal force maximums of 1.0 G and $F_{y-Wb} = 1.0$, respectively.
**Figure 3.** Step averaged velocity (A), acceleration (B) and horizontal ground reaction force (C) vs. time for the first full second of an all-out sprint of a competitive human sprinter from starting blocks. Step-averaged accelerations are large when the athlete uses both legs to push out of the starting blocks and become progressively smaller across subsequent steps. The runner’s step (i.e. time) averaged values across the first full second fall below the theorized maximums for acceleration (9.81 m·s$^{-2}$) and horizontal force application (1.0 Wb) given by the dashed horizontal lines in panels B and C, respectively.

**Figure 4.** The instantaneous vertical (gray) and horizontal (black) ground forces applied by a human sprint runner (A) and canine runner (B) over the first full second of all-out sprints from a motionless start. For both runners, the vertical component of the ground force applied exceeded the horizontal component for all steps. The time-averaged, mass-specific horizontal force applied by the Labrador retriever exceeded that of human sprinter because hind- and fore-limbs combined enabled positive horizontal, or propulsive forces to be applied for the entirety of the one-second interval. In contrast, the human runner had aerial periods between steps when ground force application was zero as well as short periods of negative horizontal force application on steps one, two and three. [Note: the human runner (Rabita et al., 2015) was instructed to give a maximal effort; the Labrador retriever (Walter & Carrier, 2011) was chasing a hot dog].

**Figure 5.** Step averaged horizontal force application (A) across the first full second of an all-out sprint for five runners performing all-out sprints from a motionless start: a 100-meter male world champion, the 100-meter male world record holder, a Labrador retriever, and two greyhound
racing dogs. The corresponding velocity vs. time profiles across the 1.0 second interval (B) are
greater for the canine than human runners. The accelerations of all five runners illustrated fall
below the theorized acceleration maximum of 1.0 G or 9.81 m·s⁻².

**Figure 6.** Push-averaged horizontal force application for human sprint athletes initiating all-out
sprints from force-instrumented starting blocks on a running track (triangles) or force-platform
mounted starting blocks in the laboratory (circles) plotted vs. each athlete’s best performance
time over the shortest standard sprint racing distance of 100 meters. In all but three of the 53
starts, the athletes horizontal force fell below the theorized maximum of 1.25 G and 12.2 m·s⁻²
for this condition (dashed horizontal line) [ \( y = -0.0926x + 1.9727; R^2 = 0.23 \) ]
Figures

Figure 1

Figure 2
Figure 3

A

![Graph A showing velocity over time with intervals labeled as air time.]

B

![Graph B showing acceleration over time with intervals labeled as Delta v.]

C

![Graph C showing force over time with intervals labeled as Delta v.]

### Graph A

- **Velocity (m/s)**
  - Y-axis from 0 to 8
  - X-axis from 0 to 1
  - Three intervals labeled as air time.

### Graph B

- **Acceleration (m/s²)**
  - Y-axis from 0 to 12
  - X-axis from 0 to 1
  - Four intervals labeled as Delta v:
    - Δv = 3.17
    - Δv = 1.14
    - Δv = 0.79
    - Δv = 0.70
  - Theoretical Limit indicated.

### Graph C

- **Force (BW)**
  - Y-axis from 0 to 1.2
  - X-axis from 0 to 1
  - Three intervals labeled as Delta v.
  - Theoretical Limit indicated.
Figure 4

A  Human

B  Quadruped

Figure 5

A  Horizontal Force

B  Velocity vs. Time
Figure 6

Theoretical Limit – Block Push

Force_y (W_b)

100-meter PR (s)

Force Plate
Starting Blocks
Optimal sprint running starts from submaximal push-off forces?

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Key words: Gravity, dynamic balance/stability, impulse, kinetics, locomotion, performance
Abstract

All-out sprint running accelerations are presumed to be optimized by maximizing the horizontal component of the ground reaction forces that determines horizontal acceleration. However, the minimum limb-ground push angles of ~ 45° observed introduce two potential horizontal force constraints: 1) large forces applied at 45° will elevate the body and prolong the aerial periods between steps when acceleration cannot occur, and 2) elevating horizontal component of the push without also elevating the vertical component will introduce bodily counterclockwise rotation (head-to-toe axis, “wheelie” effect) that would prevent or impair running. Here, we compared starting block push-off forces of ten sprint athletes under three conditions: normal sprint running starts (NS), maximal-effort dives onto a padded mat from both the normal sprint starting block position (NSD), and an inline block position with the pedals equidistant from a starting line (ILD). We hypothesized the dive conditions would remove both force constraints to allow for greater horizontal force application. We found that mean push angles fell within a narrow range of 4.2° (45.3-49.5°) and that the peak horizontal forces applied did not differ across conditions (NS=1.94±0.52, NSD=2.13±0.33, ILD=1.97±0.34 body weights). However, the average horizontal forces were greater for both dive conditions vs. the normal sprint starts (NS=0.99±0.52, NSD=1.16±0.33, ILD=1.97±0.34 Fy/Fwb). The greater average horizontal dive forces resulted from the rear-leg applying for force for relatively longer portions of the total push-off times (T_{c-rear}/T_{c-total}; NS=0.48±0.03, NSD=0.67±0.08, ILD=1.00; n=3). We conclude that all-out sprint starts are initiated with horizontal force maximums, and that sprint accelerations are predominantly limited by the time of rear-leg force application.
Introduction

Rapid accelerations of the body’s mass are required for running, jumping, hopping and other forms of locomotion. Accordingly, the mechanical basis by which rapid accelerations occur has broad relevance that spans gait, movement patterns, musculoskeletal design and performance. Maximal sprint running accelerations, in particular, have applied relevance for competitive sports that involve running, and their corresponding training and rehabilitation programs. Broad relevance undoubtedly explains why the functional basis of maximal running accelerations, has attracted attention throughout the last century (Cavagna et al., 1971; Dickinson, 1934; Furusawa et al., 1997; Gray, 1968; Hill, 1925; Rabita et al., 2015) and remains actively investigated today.

Here, we consider the limits and determinants of maximal sprint running accelerations by humans. Newtonian first principles have established that bodily motion initiated from a motionless start, is accurately described by the impulse-momentum relationship:

\[ F_{\text{avg}} \cdot t = M_b \cdot \Delta v \quad \text{eq. 1} \]

where \( F_{\text{avg}} \) is the average force, \( t \) is time force acts on the body, \( M_b \) is the body’s mass, and \( \Delta v \) is the change in the body’s velocity. In the context of sprint running, \( \Delta v \) is determined by the magnitude of action-reaction force on the ground in relation to body mass (\( F_{\text{avg}}/M_b \)) and the time of the push (\( t \)). The simplicity of this relationship indicates that regardless of conditions, bodily accelerations can be understood in terms of mass-specific forces runners apply and time of force application.

The prevailing view in the literature is that humans maximize limb extension forces to maximize \( F_{\text{avg}} \) in the horizontal direction (\( F_y \)) when pushing on the ground at the outset of an all-
out sprint effort. This intuitive view appeared early (Furusawa et al., 1997) and has evolved (Cavagna et al., 1971; Harland & Steele, 1997; Hicks et al., 2020; Mero, 1988; Morin et al., 2015; Samozino, Rabita, Dorel, Slawinski, Peyrot, Saez de Villarreal, et al., 2016) but has been largely unquestioned for a century.

There are, however, sound reasons for questioning whether this prevailing view is accurate. First, the ground forces runners apply when initiating a maximal effort from a stationary position in starting blocks, are relatively low. The per/leg ground forces sprinters apply to the starting blocks at the outset of a sprint are 2.0 to 2.5 times lower than those applied when they run at or near their maximal speeds (Figure 1). Second, runners do not appear to be able to push on the ground at angles < 45° when accelerating on level ground. This lower limit on push angle logically limits the horizontal component of the ground force ($F_y$) to a value ≈ equal to the vertical component of the push. The vertical component must be large enough to offset gravity and support the body’s mass, i.e. $\approx mg$ (where $MG = 1.0 \times$ body weight $= F_z/F_{Wh}$) on a time-averaged basis. However, the vertical component should also not be too large. This follows from legged accelerations being compromised by any unnecessary time in the air between steps – simply because the body’s velocity in the air is constant, and does not accelerate, when the legs are not pushing on the ground.

The possibility that the ground forces runners apply might be constrained by the need to not substantially exceed body mass and introduce unnecessary aerial time has been broached by only two groups of scholars. The first literature occurrence was in advance of the Apollo missions a half century ago when (Margaria & Cavagna, 1964) concluded that sprint performances, including acceleration would be compromised in low gravity environments, in part due to this factor. More recently, experimental work by Kugler & Janshen, 2010 led them to
speculate that the benefits of short aerial times could conceivably lead rapidly accelerating runners to apply submaximal ground forces.

Here, we tested the simple hypothesis that all-out sprint starts are initiated with submaximal block push-off forces. We did so by comparing all-out sprint running accelerations to those under two maximal-effort dive conditions. The dive conditions chosen were designed to remove the potential force constraints imposed by 45° take-off angles and need for short aerial times. Push-off mechanics during three conditions were compared: 1) conventional sprint starts (normal sprint starts, NS) from force plate mounted starting blocks, 2) maximal-effort dives from the normal starting block position onto a padded mat, and 3) maximal-effort dives from inline, or parallel block settings that allowed subjects to push simultaneously using both legs (ILD).

We predicted that the average horizontal and total force applied to the blocks (and horizontal acceleration per eq. 1) would be lowest in the sprint running start condition, intermediate in the normal block dive, and greatest for the inline dive condition that enables simultaneous right and left leg pushes.
Methods

Participants

Ten male sprinters (Age: 29.3 ± 6.8 years old; Mass: 76.7 ± 7.12 kg; Height: 1.72 ± 0.05 m) of mixed athletic ability (100-m personal best: 10.94 ± 0.69 s) provided written, informed consent to participate in the study, which was approved by the Institutional Review Board at Southern University [protocol 2013-038].

Experimental Conditions

Participants completed maximal-effort trials under three experimental conditions: Normal-sprint Start (NS), Normal Start Dive (NSD), and In-Line Dive (ILD) as illustrated in Figure 2. The NS condition involved a maximal effort sprint initiated from the block positions subjects chose based on established personal preferences. For the NSD, subjects also started from the same personally preferred sprint start block positions. From this starting position, they executed a maximal effort dive with a prone landing onto a 2.4 x 1.2 x 0.3-meter foam mat. The ILD condition was initiated from a parallel block starting position for all subjects. In this condition also, subjects executed a maximal effort dive with a prone landing onto a sliding mat. Participants alternated between trials and conditions, performing six trials for each condition with instruction to take full recovery between trials.

All trials were conducted in the Applied Physiology Laboratory at SMU equipped with a 1-meter-wide running lane within 20-meters of linear running space. Participants began from and sprinted over a series of integrated force platforms (Bertec, Model #FP9090-15-4000, 0.9 × 0.9 m) before transitioning to a rubber flooring extending through the sprinting lane. A standard starting
block system (Cantabrian Catapult™) was modified (Custom Scientific™) to bolt securely to the platforms.

Ground reaction force data were collected using the integrated force platforms, and the timing and kinetic data were synchronized through a National Instruments PCIe-6323 data acquisition board (32 analog inputs, 250 kS/s, 16-bit resolution) and LabVIEW (2011) software, sampling at 1000 Hz. Force data were post-filtered using a low-pass, fourth-order, zero-phase-shift Butterworth filter with a cutoff frequency of 25 Hz. A start trigger was devised using the force platform to minimize timing error due to variations in start techniques across the different conditions. Specifically, timing commenced once the participant generated 50 N of horizontal force.

*Individual-limb vs. Dual-limb Force Data*

Three of the ten participants elected block pedal positions for rear and front legs that more than 35 cm apart. This relatively long distance resulted in the front and rear feet spanning platforms one and two in our three-platform system. For these subjects only, we were able to acquire rear-limb force-time data from platform one and front-limb force-time data from platform two. For the seven subjects who elected closer pedal positions, individual-limb data from the rear and front limbs were not available.

*Procedure*

Participants executed a series of sprints alternating under three different starting conditions: NS, NSD, and ILD, performing six trials for each condition, resulting in a total of eighteen trials per participant. Data analysis incorporated all trials performed by participants.
To standardize all trials, participants were outfitted with appropriately sized rubber track flats, a black compression shirt, and black compression pants before engaging in a 10–15-minute dynamic warm-up. During the warm-up, participants were briefed on the general set-up guidelines tailored to each starting condition. A brief demonstration was given to clarify the set-up procedure, followed by sub-maximal and maximal practice sprints to familiarize participants with the testing protocol.

Post warm-up, participants were instructed: “The remaining sprints will be completed with maximum effort”. For each trial, participants positioned themselves in the block-starting position and, upon readiness, executed the sprint with maximal effort. For the dive trials, participants were instructed: “For these trials, imagine you are trying to dive over the mat at the start signal. Give it your maximum effort.” They positioned themselves in the block-starting position, and upon readiness and the start signal, performed the sprint with maximal effort, focusing on the cue to "dive over the mat" to emphasize maximal exertion. Verbal encouragement was provided throughout the tests.

Data Analysis
The force data were processed using a custom MATLAB script designed to acquire the following variables: the duration of the block push phase ($T_c$), average horizontal force ($F_y$), peak horizontal force ($F_{y-peak}$), average vertical force ($F_z$), resultant force magnitude ($F_{tot}$), resultant angle ($\angle$GRF) and horizontal impulse ($J_y$). The resultant force magnitude ($F_{tot}$) was determined using the Pythagorean theorem:

$$F_{tot} = \sqrt{F_y^2 + F_z^2}$$
Impulses in the horizontal direction were calculated by integrating the respective force-time curves over the block push duration:

\[ J_y = \int_0^{T_c} F_y dt \]

For the three dual force limb subjects, the following additional variables were determined: the time of rear-leg force application \( T_{c\text{-rear}} \), the fraction of the total time the rear leg contributed force \( T_{c\text{-rear}}/T_{c\text{-total}} \), and the average horizontal force per leg \( F_y/\text{leg} \) which was calculated by dividing mean horizontal force by the average number of legs contributing force across the duration of the push in each condition \( = 1 + \frac{T_{c\text{-rear}}}{T_{c\text{-total}}} \).

**Ensemble-averaged Waveforms**

Mean impulse, or force-time patterns for the push-off forces acquired from the ten participants were ensemble averaged for each condition to obtain representative group mean force-time waveforms for each condition. The ensembles were generated per conventions by slight positive or negative adjustments to match the end time for each subject to the mean end time of the full group for each condition.

**Statistical Analysis**

The following mechanical variables were analyzed across the three experimental conditions using a repeated measures ANOVA: \( F_y, F_z, F_{\text{tot}}, T_c, J_y \), and peak force at an *a priori* alpha level of \( p < 0.05 \) and Bonferroni comparisons of post-hoc means also at \( \alpha < 0.05 \). The mean condition maximums for peak horizontal forces \( (F_y\text{-peak}/W_b) \) were also tested by repeated measures ANOVA at the same probability level. A multivariate analysis of variance, MANOVA was also
used to test the effect of condition on the following set of variables: $F_y$, $F_z$, $F_{tot}$, $T_c$, and $J_y$ due to their potential interdependence.

For the subgroup of three subjects for whom individual limb force data was available, means individual limb data was determined for $F_y$, $F_z$, $F_{tot}$, $T_c$, and $J_y$. Repeated measures ANOVA was used to evaluate the time of rear-leg force block application across the three conditions and compare $F_y$ and $J_y$. 
Results

Mean Force, Time, and Impulse Data

The mean force-time or impulse patterns from the ten participants for $F_y$ and $F_z$ in each experimental condition appear in Figure 3. The largely parallel $F_y$ and $F_z$ patterns of force application over time were longest for the NS condition, intermediate for the NSD condition, and most brief for the ILD condition (Figure 4, leftmost panel). The ensemble-averaged peak forces for both $F_y$ and $F_z$ were similar across the three conditions. The peak horizontal forces in the three conditions were nearly equal, falling in a narrow range between 1.60 and 1.75 body weights across the three conditions. The respective horizontal impulses, $F_y$, which correspond to the areas under each curve, differed primarily in accordance with how long force values near the peak were maintained as the push proceeded. Participants applied near-peak forces most briefly for the NS condition, did so intermediate durations for the NSD condition, and did so for nearly the entirety of the ILD condition.

The block horizontal exit velocities physically determined by the horizontal impulse $J_y$ (eq. 1) were slowest for $NS = 3.33 \pm 0.27 \text{ m/s}^{-1}$, intermediate for $NSD = 3.74 \pm 0.29 \text{ m/s}^{-1}$, and greatest for $ILD = 3.86 \pm 0.34 \text{ m/s}^{-1}$. Because the mean vertical forces, $F_z$ were slightly greater than the mean horizontal forces, the mean angle of block force application was above 45° for all three conditions and varied within a narrow range of 4.2°: NS = 49.5 ± 2.4°, NSD = 46.6 ± 3.7°, ILD = 45.3 ± 4.2°.

Hypothesis Test Results

In addition to $T_c$, mean ± SD values for the ten participants for $F_y$, $F_z$, $F_{tot}$ (center panel), and $J_y$, $J_z$ and $J_{tot}$ (rightmost panel) appear in Figure 4. Repeated measures ANOVA identified
significant main effects for all variables across experimental conditions for horizontal force, $F_y$, and impulse, $J_y$, and total force, $F_{tot}$ that were significant ($p < 0.001$) with Bonferroni post-hoc comparisons indicating the three condition means differed significantly from one another. The repeated measures ANOVA also indicated a significant main effect for push time, $T_c$, with post-hoc comparisons indicating both NS and NSD differed from ILD.

Repeated measures ANOVA for vertical force, $F_z$, and peak force indicated no main effect of condition for either variable.

MANOVA analysis for the suite of dependent variables ($T_c, F_y, F_z, F_{tot}, J_y$) was also significant across conditions. Each of the individual variable MANOVA post-hoc tests were significant at $p < 0.01$. Specifically, follow-up univariate ANOVAs revealed significant effects of condition on $T_c$, $F(2, 27) = 12.235$, $p = 0.000165$; $J_y$, $F(2, 27) = 8.3906$, $p = 0.001466$; $F_y$, $F(2, 27) = 20.728$, $p = 3.511e-06$; $F_z$, $F(2, 27) = 10.287$, $p = 0.0004775$; $F_{tot}$, $F(2, 27) = 24.31$, $p = 9.159e-07$; and $J_{tot}$, $F(2, 27) = 6.4427$, $p = 0.005157$. These results indicate that the experimental conditions significantly influenced the sprinting mechanics in terms of block push duration, impulse, and force components. No significant differences were observed for $J_z$.

*Individual-Leg Force Subject Data*

The mean data for the subgroup of three subjects for whom independent rear and front leg force data are available appear for all the dependent variables appear in Figure 4 as circles in the appropriate variable column spaces. The means from the subgroup corresponded closely to the overall means with minimal variance. Across condition differences in mean value for the three subjects paralleled the across condition differences in the overall means almost exactly.
The force-time patterns for each of the three individual-leg force subjects for each condition appear in the three columns of Figure 5. For each of the three the duration of the push by the rear leg became more prolonged from the NS condition (top row) to the NSD condition (middle column) to the ILD column. The duration for which the athletes were able to maintain forces close to their individual total peaks across the duration of the block push closely corresponded to the duration of the push by the rear leg.
Discussion

We set out to test the hypothesis that all-out sprint running starts are optimized with submaximal push-off forces and did so by implementing all-out dive accelerations that we expected would remove both theorized force constraints: the minimum push angle of 45° and the need to minimize the time in the air before the first running step. Contrary to our expectation, our participants did not opt for appreciably lower push and take-off angles in the dive conditions; they opted for nearly the same push orientation as during sprint running [NS = 49.5 ± 2.4°, NSD = 46.6 ± 3.7°, ILD = 45.3 ± 4.2°]. The second constraint, removal of the need to minimize time in the air was successfully removed by the dive conditions as the subjects landed on the mat chest-first in prone positions (View Conditions Here). The outcome variable we first evaluated, the average horizontal push-off forces, followed the pattern we predicted at the outset of the study (Figure 4, middle panel). The mean horizontal push-off forces our participants exerted were smallest in the normal sprint running condition (NS $F_y = 0.99 ± 0.10$) with both the normal start dive and inline dive forces being significantly higher (NSD $F_y = 1.17 ± 0.11$; ILD $F_y = 1.38 ± 0.18$). Despite this apparently direct support for our hypothesis, we rejected it upon further analysis. The peak horizontal forces, which in this instance, may arguably be a better indicator of limb pushing force maximums did not differ across conditions (Table 1; Figure 4 condition ensembles, leftmost panel). Additionally, when we fully incorporated the duration, and therefore the force contribution of the rear leg to the total, the average force/leg (Figure 5, Table 2) was identical across the three conditions. Thus, the mean horizontal sprint running forces were lower only because the duration of the push from the rear leg was so brief. We conclude that maximal sprint running accelerations: 1) are executed with maximal limb push-off forces, and 2) are primarily limited by the time of rear leg force application.
Block Push Forces Across Conditions

Our horizontal force data across conditions are well illustrated by the ensemble averages appearing in the left panel of Figure 4. The similarity of the peak horizontal forces across the three conditions, and differences in the ability to maintain near-peak force levels as the block pushes proceeded are both apparent. In the normal sprint start, the horizontal force applied peaks early and falls then rapidly to values of roughly half the peak for the remainder of the push. The force peak for the NSD condition also occurs very early in the push, but is maintained longer before dropping off gradually, and the peak occurs latest in the ILD condition, but near-peak forces are sustained throughout nearly the entire push. Because the impulse, per eq. 1 (F_{avg} \cdot t) is what determines the change in body’s velocity, here from zero to the block exit velocity, is mathematically equal to the areas under the respective condition curves, the differences apparent in the ensemble averaged curves illustrate why the average horizontal forces, and corresponding block exit velocities were greater for both dive conditions. The peak or near-peak forces were better sustained across the duration of the push for both dives vs. the run condition.

One consequence of the ability to sustain near-peak forces for a longer portion of the block push in the dive conditions was that the upper limit for maximum sprint running accelerations was exceeded. Previously, athletic sprinters, whether humans, canine or even fastest feline species like cheetahs (S. B. Williams et al., 2009; Wilson et al., 2013) have not accelerated at rates above 1.0 G or of 9.81 m·s^{-2}, at the outset of all-out sprints. Here, that 1.0 G limit was comfortably exceeded by our participants in both dive conditions. Specifically, the push-averaged accelerations of our participants for the NSD and ILD conditions were 11.4 ± 1.1 and 13.6 ± 1.8 m·s^{-2}, respectively. Even though the total push time, T_{c-total}, was slightly reduced for both dive conditions vs. sprint running (left panel, Figure 4), the push-averaged accelerations
of our participants for the NSD and ILD conditions resulted in horizontal block exit velocities of 3.74 ± 0.29 and 3.86 ± 0.34 m/s, respectively. To put this in perspective, our most forceful athlete in the ILD condition was able to exit the starting blocks roughly 1/3rd faster in the ILD condition than the block clearance velocity measured for the fastest sprinter in human history (4.6 vs. 3.4 m·s⁻¹, from Willwacher et al., 2016).

The ensemble averaged force-time patterns for the three conditions illustrate the that dive conditions somehow enabled near-peak forces to be maintained across the duration of the block push, but they do not explain how. Undoubtedly, this prolongation ability clearly explains why the mean horizontal forces in the dive conditions exceeded the run conditions even though the measured peaks were not statistically or appreciably different numerically (Table 1). Of course, the key question is how the dive condition mechanics allowed for force prolongation that running did not. The best evidence to evaluate this is the timing data for the duration of the back limb push across the three conditions. These data were only available on the subset of three subjects for whom we were able to measure force independently for both limbs due to elongated pedal position preferences that resulted in rear and front pedals being on different force platforms. The rear leg and total force-time data of each of the three in each condition appear in Figure 5. These data illustrate that the duration of the rear leg push in the NS condition is just under half of the total block push time for the NS condition Figure 5 top row) as has been widely reported (Harland & Steele, 1997; Henry, 1952; Mero, 1988; Willwacher et al., 2016), extends to just under 3/4th of the total for NSD (Figure 5, middle row), and to the entire push or 100% for the ILD condition (Figure 5, bottom row). These individual limb force data make clear the direct relationship between the prolongation of the rear leg push, and the duration of the time the $F_y$ force values remained at near-peak force levels in the different conditions.
Individual Limb Force and Time Data

The availability of these data for only a subset of three subjects does raise the reasonable question of representativeness for the entire group. In the case of the NS condition, our data match those of a number of other investigators who published individual limb block force data, all of whom reported fractional values between 0.40 and 0.50 of the full push (Čoh et al., 1998, 2017; Henry, 1934.; Slawinski et al., 2010; Willwacher et al., 2016) that are in good agreement with the 0.48±0.03 measured for our three subjects. More thorough and compelling for the germane consideration here is that $T_c$, $F_y$, $F_z$, $F_{tot}$, and impulse means for the subset of three subjects (open circles, Figure 4) closely matched the means for the full group across all conditions. Equally important to the question of the representativeness of the individual limb force-time means for the entire group is that the complex patterns of change for the different variables across conditions for the whole group and the subgroup of three occurred in parallel. These observations provide strong evidence that the subgroup and full group adopted similar rear-leg push-off strategies across conditions.

One benefit of timing data from the rear limb was that it enabled us to incorporate the rear leg fractional push timing ($n=3$) to determine the average number of limbs active across the full push (Table 2). The limb number average, in turn enabled to quantify the mean $F_y$/leg. This resulted in $F_y$/leg values across the three conditions being nearly identical (Table 2), agreeing to within ±2% and two one-hundredths of $F_{Wb}$ on average ($F_y$/leg =0.67±0.01, $n=10$). When we repeated the calculation using the $F_y$ mean from only the three subjects on whom we had individual limb data, the overall mean was slightly higher ($F_y$/leg =0.73±0.01, range=0.72 to 0.74, $n=3$) but the agreement was equally close. The closeness of these values across conditions provides compelling support for two conclusions: first, that the difference in the average force
means for $F_y$ across run and dive conditions resulted entirely from rear-limb timing differences, and second, that forces from both limbs were almost certainly maximal.

**Why Are Leg Forces So Relatively Low for Block Starts vs. Maximum Velocity Sprinting?**

One of the underpinnings of the submaximal force for all-out sprint acceleration hypothesis was how low the measured limb force values are, particularly in comparison those measured during fast sprinting at relatively constant speeds (Figure 1). As noted at the outset, the block push-off forces are one-third or less than the limb-ground forces during fast sprinting. The data in Figure 1 are resultant forces (i.e. include both $F_z$ and $F_y$ per $F_{tot}$ here) and therefore are moderately higher in absolute terms than the $F_y$, horizontal-only forces that have been a primary focus here. However, the resultant forces here for normal sprint accelerations are in full agreement with those appearing for block starts in Figure 1 in the rightmost panel with a mean = 1.0 x $F_{WB}$. How can a 3.5-fold offset in limb forces be explained if the forces in both cases are deemed true conditions maximums?

We investigated the first part of the question for maximal speed sprinting, repeatedly finding that runners who are able to apply greater mass-specific forces can run faster (Weyand et al., 2000, 2010). We also found that the characteristic “high-knee” gait pattern that competitive sprinters adopt enables them to achieve a high lower-limb velocities into the ground with a rapid deceleration on impact (Clark et al., 2017). Obviously, block starts do not allow any impact forces to be applied since the feet are touching the blocks prior to the force application event. Additionally, the limb muscles acting at the ankle and knee operate largely through cycles of stretch on initial ground contact, and subsequent recoil which assists with each take-off. In contrast, the muscles acting across the ankle, knee and hip joints only extend while pushing on
the starting blocks to initiate acceleration. They do so via active muscle shortening that acts to straighten the joints, extend the limb and push on the starting blocks. The forces generated by fully active muscle under these different conditions: shortening vs. stretch-recoil mechanics are known to differ by a factor of three when examined under controlled circumstances in isolated preparations outside the body. Consequently, the condition maximums observed fully correspond to those expected under the respective conditions.

Prior sprint running experiments at fast speeds also allowed us to identify how critically brief limb-ground force application periods become (Weyand et al., 2000, 2010). This is particularly true for the swiftest sprinters whose foot-ground contact times often drop below 0.1 or even 0.09 seconds (Figure 1). A priori, given the relatively low forces and long times of force application times that are nearly four times longer than those at fast speeds, we did not anticipate (eq. 1) that the primary limitation to both accelerating the body and attaining faster top speeds would be the time available for force application (Figure 5) as our data ultimately indicated.
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https://doi.org/10.1080/10671188.1952.10624871


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https://doi.org/10.1016/j.jbiomech.2015.07.009


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**Author Contributions**

LCB: conceptualization, data acquisition, data analysis, figure preparation, writing and editing.

PGW: conceptualization, data acquisition, data analysis, writing and editing. Both authors have approved the manuscript and take responsibility for the contents.

**Conflict of Interest**

The authors declare no competing interests.

**Funding**

This work was made possible by a Fairess Simmons Doctoral Fellowship to LCB and the Glenn Simmons Endowment to PGW.

**Acknowledgments**

We extend our gratitude to Sunil Prajapati for timely assistance in figure preparation, to Kenneth Clark, Laurence Ryan, and Andrew Udofa for engaging in early scientific discussions, and to Rae Edwards, Darryl Woodson, and Jon McDowell for their significant help with subject recruitment.
### Tables

**Table 1. Peak Horizontal Forces [Mean ± SD]**

<table>
<thead>
<tr>
<th></th>
<th>Force (\frac{F_{\text{y,peak}}}{F_{\text{Wh}}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Start</td>
<td>1.94 ± 0.52</td>
</tr>
<tr>
<td>Normal Start Dive</td>
<td>2.13 ± 0.33</td>
</tr>
<tr>
<td>Inline Dive</td>
<td>1.97 ± 0.34</td>
</tr>
</tbody>
</table>
## Table 2. Average Horizontal Force, Push Times and Force/Leg

<table>
<thead>
<tr>
<th>Condition</th>
<th>( F_y ) ((F_y/F_{Wb}))</th>
<th>( T_{c\text{-rear}} ) (s)</th>
<th>( T_{c\text{-total}} ) (s)</th>
<th>( T_{c\text{-rear}}/T_{c\text{-Tot}} ) (ratio)</th>
<th>Legs/Push (1 + ratio)</th>
<th>( F_y/\text{Leg} ) ((F_y/F_{Wb}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>0.99 ± 0.52</td>
<td>0.19 ± 0.02</td>
<td>0.39 ± 0.01</td>
<td>0.48 ± 0.03</td>
<td>1.48 ± 0.03</td>
<td>0.67 ± 0.01</td>
</tr>
<tr>
<td>NSD</td>
<td>1.16 ± 0.33</td>
<td>0.27 ± 0.02</td>
<td>0.38 ± 0.02</td>
<td>0.73 ± 0.08</td>
<td>1.73 ± 0.08</td>
<td>0.67 ± 0.03</td>
</tr>
<tr>
<td>ILD</td>
<td>1.38 ± 0.34</td>
<td>0.31 ± 0.05</td>
<td>0.31 ± 0.05</td>
<td>1.0</td>
<td>2.0</td>
<td>0.69 ± 0.00</td>
</tr>
</tbody>
</table>

The \( F_y \) values represent the mean values from \( n=10 \); the single leg timing data \((T_{c\text{-rear}}, T_{c\text{-total}})\) is from the subset of \( n=3 \) for whom single leg data was available.
Figure Captions

Figure 1. The total, or resultant, running ground reaction force profile vs. time for a single steady-speed sprinting running step at 11.5 m·s⁻¹ (upper left panel), and during the initial push from starting blocks at the outset of a sprint (lower left panel). The mean ground force/leg in body weight units applied to the ground during single steps from different sprint athletes vs. body mass during both steady-speed sprinting steps at speeds above 9.0 m·s⁻¹ (closed gray circles, rightmost panel) is more than two times larger vs. the per/leg ground force applied during blocks starts (closed black circles, rightmost panel). [Note: the per/leg force values for the block starts represent the total resultant force/1.5 since the back leg, on average, contributes force only during the first half of the block push time per lower left panel].

Figure 2. Illustrations of the set and exit positions for the three experimental conditions: normal sprint start (top), maximal-effort dive executed from sprint start block position (middle), and maximal effort dive executed from the inline or parallel block position (bottom).

Figure 3. Ensemble averaged horizontal (F_y, left) and vertical (F_z, right) force-time profiles (i.e. impulses) of the ten subjects for each experimental condition. The impulses determining the horizontal exit velocities (F_y panel) as provided by the area beneath each curve, were greatest for the inline dive condition, intermediate for the normal start dive, and smallest for the normal sprint start condition. The peak F_y forces for the three respective conditions were nearly equal while the average forces differed due to the differing force-time patterns.
Figure 4. Time (top panel), Block force in units of the body’s weight (center panel) and impulses in body weight • seconds (bottom panel) for the three experimental conditions. Mean horizontal and vertical forces and impulses were greater for the normal start and inline start dives the time of force application was shorter vs. the normal start condition. The open circles represent the mean values of the subgroup of three subjects for whom individual leg force data was available. The # indicates a significant difference vs. NS condition; x indicates a significant difference vs. NSD condition. Note that subgroup means for the respective variables closely paralleled those of the entire group of ten subjects.

Figure 5. Total and rear leg only horizontal block force vs. time for each condition (top row – normal start, middle row (normal start dive) and bottom row (inline dive) for each individual for whom individual leg force data was available. Note that the time of the back leg push was shortest for the normal sprint.
Figures

Figure 1
Figure 2

NS

NSD

ILD

Figure 3

$F_y$

$F_z$

Force (W,\text{n})

Time (m$^{-1}$s$^{-1}$)
Figure 4
Figure 5

![Graph showing Force_y (Wb) vs Time (m/s) for different conditions: NS, NSD, and ILD.](image-url)
Why do sprinters prefer staggered-stance block starting positions?

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Key words: performance, force application, biomechanics, gait, impulse, locomotion
Abstract

Competitive sprint runners initiate their races with their right and left feet in starting blocks at significantly different distances from the starting line. Although this practice is essentially universal and supported by long-standing literature recommendations to separate the feet, typically by 30 to 50 cm, the mechanical benefit of doing so to sprint acceleration is unclear. This is particularly so vs. an inline start with the feet adjacent and equidistant from the start. At least in theory, the inline position would allow simultaneous maximal limb extensions resulting in more rapid acceleration and faster exit from the blocks. Here we tested the sprint starts of 10 male sprint athletes who spanned a range of competitive levels using a 2.7-meter series of force platforms that permitted measurement of the initial push in the starting blocks (Step 0) and the subsequent step (Step 1). The athletes started from either their normal or preferred sprint starting position (NS) or the inline block (ILS) pedal configuration. Across conditions, we found block exit angles and post-block aerial times were virtually identical, that the horizontal block forces applied were equal, but that time of force application and impulses were significantly smaller in the ILS condition. Consequently, block exit velocities that were substantially slower in the ILS vs. NS condition (2.88 vs 3.33 m·s⁻¹, respectively). We conclude that ILS block pedal positions reduce the time of block force application and block exit velocities.
Introduction

By preference, instruction, or perhaps convention, athletes engaged in foot races have long adopted starting positions with one foot positioned ahead of the other. In standing starts, the advantage, or arguably necessity, of doing so, is mechanically obvious. Forward and balanced acceleration is not possible if the body’s mass is not positioned in front of the foot pushing on the ground. However, athletes have adopted the staggered foot starting position ~ universally since the introduction of starting blocks in the middle of the last century. Notably, even prior to legalization of the use of starting blocks in competition just prior to 1940, athletes including Jesse Owens, dug holes in the track to improve their ability to push-off at the outset of races. In the pre-blocks era also, athletes dug holes that positioned right and left feet at appreciably different distances from the starting line. The consistency of this practice for well over eight decades provides strong observational evidence that the practice is somehow advantageous. Like athlete preferences, the scientific literature on this topic is consistent and also in agreement with standard practice. Studies on sprint starting foot positioning, although highly specific and arguably niched, have an active history that dates to the origins of starting blocks (Dickinson, 1934; Henry, 1934; Kistler, 1934; Schot & Knutzen, 1992; Sigerseth & Grinaker, 1962; Slawinski et al., 2012). Several of the early investigators engineered force instrumented blocks for the explicit purpose of studying sprint starts (Henry, 1934; Kistler, 1934). The classic and subsequent literature has consistently divided foot separation distances into three categories: bunched (<30 cm), intermediate (30 to 50 cm) and elongated (>50 cm). With nearly complete consistency, investigators have concluded that intermediate foot positioning results in the best overall starts from a competitive standpoint.
The basis for this consensus is that the block force data acquired in many of these studies identify a trade-off between the longer force application times and greater of block exit velocities provided by the elongated stance vs. shorter force application times and slower, but quicker block exits from the bunched position. Multiple investigators have cited this trade-off (Bezodis et al., 2019; Harland & Steele, 1997; Henry, 1934; Slawinski et al., 2012) to explain why the shortest times to 5 and 10 meters (Henry, 1934; Sigerseth & Grinaker, 1962; Slawinski et al., 2012), have resulted from intermediate, rather than elongated or bunched foot positioning. In this respect, a well-supported literature consensus exists to indicate that bunched starting positions compromise both block forces and impulses (Bezodis et al., 2019; Harland & Steele, 1997; Henry, 1934; Slawinski et al., 2012). However, all these studies enrolled competitive track athletes or physically active subjects; none examined athletes who were among the best sprinters or sprint starters in the world.

From a mechanical perspective, the purported benefit of staggering feet for sprint starts from blocks seems reasonable to revisit for several reasons. The obvious objective of sprint races is to move the body forward as quickly as possible. Considered in isolation, this objective would theoretically be best served by positioning both limbs to provide maximal, simultaneous pushes. Simultaneous maximal pushes from both limbs would accelerate the body’s mass more rapidly, and in less time after the start. Equally or perhaps more importantly, our prior experimental work (chapter 3) indicates that simultaneously pushing with both legs can and does accelerate the body significantly more rapidly than is possible with intermediate foot spacing. We established this for “single shot” dives from sprint starting blocks onto a padded mat. At least for the dive maneuver from identical starting positions, simultaneous pushes by right and
left legs can accelerate the body’s mass 1.5 times more rapidly than the best sprinter runners in the world do (Willwacher et al., 2016).

So, we wondered what factors might be present when athletes run, rather than dive after exiting the starting blocks, that would interfere with maximal limb extensor forces, impulses and acceleration performance, particularly from bunched or inline starting positions. Conceivably, wider stances with one more anteriorly positioned foot would allow for a flatter trajectory of the center of mass as it passes the front foot in the latter phase of the block push. Conversely, the absence of a front foot may therefore force runners into a more vertical push and exit from the blocks. Accordingly, we hypothesized that inline starting block pedal positions (i.e. feet equidistant from a starting line) would result in the following negative consequences in the initial steps of a sprint run after leaving the blocks: 1) a more vertical push on the blocks and exit trajectory, 2) a longer aerial period between block exit and contact for the first step, and 3) limb and body positions that compromise first step force application after leaving the blocks.

Our secondary goal was somewhat exploratory, we set out to acquire the block spacing distances used by international-class sprinters, particularly those whose performances established them as elite starters. We did so to evaluate whether practices by the practices of the best sprint performers align with longstanding literature recommendations, or perhaps do not.
Methods

Participants

Ten male sprinters (Age: 29.3 ± 6.8 years old; Mass: 76.7 ± 7.12 kg; Height: 1.72 ± 0.05 m) who varied in competitive level from local to regional and national class athletes (100-m personal best: 10.94 ± 0.69 s) volunteered and provided written, informed consent in accordance with the protocol approved by the Institutional Review Board at Southern Methodist University [protocol 2013-038]. All participants were experienced with track blocks, with competitive experience at the high school, collegiate, and/or professional level.

Procedures and Data Acquisition

Subjects performed a series of sprints alternating between two starting conditions that differed in foot positioning: normal start (NS) and inline start (ILS), performing six trials for each condition, resulting in a total of twelve trials per participant. Participants were instructed to take full recovery between trials to avoid fatigue.

The NS configuration was set according to each athlete's customary starting block preference. For the ILS configuration, athletes adjusted their starting position by moving the front pedal to the back position, as the reverse was reported to be too uncomfortable. Before collecting data, athletes were habituated to the ILS condition through a series of practice trials to ensure familiarity and consistency in their performance.

For standardization purposes, participants were provided with rubber track flats in their shoe size, compression tops and short pants before warming up for 10–15-minutes. During the
warm-up, participants were informed of the guidelines for each starting condition. A brief demonstration was given, followed by the performance of sub-maximal and maximal practice sprints for familiarization with the test protocol.

Once subjects completed a dynamic warm-up, they were instructed: “The remaining sprints will be completed with maximum effort.” For each trial, participants positioned themselves into the starting blocks positioned according to foot placement condition and, upon self-initiated starts executed the sprint with maximal effort. Verbal encouragement was provided.

Five-meter timing data were collected with a Banner Engineering (Model #QS186LE Laser Emitters and Model #QS18 Receivers) timing system that sampled at 1000 Hz with a response time of < 1.0 ms. This system was equipped with dual beams that improve timing accuracy by requiring simultaneous blockage of both lasers to record the time. This design ensures that only the participant’s trunk rather than arms, legs or head triggers the timing system (Earp & Newton, 2012). The lasers were positioned five meters from the start line, with the upper and lower beams placed at heights of respective heights of 115 cm and 85 cm above the floor.

Force and time data were collected from the integrated force platform system with the data streams synchronized through a National Instruments PCle-6323 data acquisition board (32 analog inputs, 250 kS/s, 16-bit resolution) running LabVIEW (2011) software, sampling at a frequency of 1000 Hz. Force data were post-filtered using a low-pass, fourth-order, zero-phase-shift Butterworth filter with a cutoff frequency of 25 Hz. A starting trigger using of 50 N on horizontal force channel was implemented to reduce timing error. Data for the push out of the starting blocks, designated here as “Step 0” and the first step after on the force platforms after the starting blocks, designated as “Step 1” were acquired.
The data from the normal foot placement starting position was reported in the prior chapter of this document.

*Ensemble-averaged Waveforms*

The mean force-time patterns for the push-off forces (i.e impulses) acquired from the ten participants both foot placement conditions were ensemble averaged to obtain representative group mean force-time waveforms for each. The time scales of individual waveforms were adjusted to equal of the respective condition means for this purpose.

*Data Analysis*

Force and time data were processed using custom MATLAB scripts to compute the output variables of interest. Variables included were time of the block push phase \( T_c \), average horizontal force \( F_y \), average vertical force \( F_z \), resultant force magnitude \( F_{tot} \), resultant angle \( \angle GRF \) and horizontal impulse \( J_y \). Total force magnitude \( F_{tot} \) or resultant force, was determined in accordance with the Pythagorean theorem:

\[
F_{tot} = \sqrt{F_y^2 + F_z^2}
\]

Horizontal impulses were calculated by integrating the force-time curves acquired over the duration of the block push:

\[
J_y = \int_0^{T_c} F_y \, dt
\]
The variables analyzed statistically across the two-foot placement conditions (NS and ILS) were: average vertical and horizontal forces, resultant force magnitude and angle, respective impulses, and push duration.

*Field Block Spacing Data*

Digital images of Olympic, World Championship and other international athletic competitions were acquired from published sources for the purpose of determining the foot placements used by the world-class short sprint specialists at the shortest respective indoor and outdoor sprint distances of 60 and 100 meters. We attempted to acquire data for the fastest eight athletes on World Athletics Male Indoor All-time 60-meter performance list. We also acquired data for two world-record holding 100-meter specialists known for their starting performances, but who seldom competed at the indoor 60-meter distance. One finished first in the men’s 100-meter world championship race in 1987 (time = 9.83 s), the other was the 2017 male world champion at 100-meters (personal best 9.74 s, #5 on the all-time 100-meter performers list).

Foot placements were determined using the known length of the starting block center beam as a length reference. Only high-resolution digital images were used to estimate block pedal positions.

*Statistical Analysis*

To evaluate the effects of the different foot placement starting conditions (NS and ILS) on push-off mechanics, a series of paired t-tests were conducted for the following variables: impulse of
the horizontal force \( (J_{y\text{-step0}}) \), time in the air \( (T_{air}) \), impulse during the first step \( (J_{y\text{-step1}}) \), time to cover 5 meters \( (5m \text{ time}) \), and impulse over 5 meters \( (5 \text{ m impulse}) \). The alpha level was set at 0.05 for all statistical tests. The paired t-tests comparing the mean values for NS and ILS conditions across the ten participants \( (n=10) \) were performed using Microsoft Excel. The \emph{a priori} level of statistical significance was set at \( p < 0.05 \).
Results

Block Spacing Data

The mean ± SD preferred foot placement distances as well as the distances chosen by each of the ten participants appear in Figure 2 (leftmost bar). The group mean was just over 31 cm and therefore at the lower end of the literature defined intermediate spacing designation of 30 to 50 cm (lower limit identified by the shaded horizontal bar). However, most of our subjects selected block pedal distances that conform to the shorter “bunched” literature designation. The mean distance estimated for the eight male finalists who competed in the 2013 World Athletics Championship in Moscow in 2013 (middle bar) was more than 4 cm shorter than the lower limit for the intermediate foot spacing categorization, and therefore fell into the “bunched” categorization distance region of < 30 cm. The additional position distances acquired for world-class male sprinters established also as premiere starters also fell below the intermediate minimum and therefore in the bunched category.

Mean Force, Time, and Impulse Data: Step 0

The ensemble averaged force-time waveforms for horizontal and vertical force applied to the blocks in both starting positions appear in Figure 3. The force vs. time patterns vary primarily in their duration with the ILS condition being substantially briefer. The mean forces are largely similar on average across the ensembles. The mean magnitude and orientation of the block pushes in the respective conditions was literally all but identical as can be seen from the superimposition of the vectors on one another in Figure 4. The push angles for the two conditions differed by 0.1° (NS = 49.5° vs. ILS = 49.4°).
The mean force and time components of the block push are presented separately in the left column panels in Figure 5 for both starting positions (Step 0). The shorter mean push time (top panel, p<0.01) while applying the same average block force (middle panel) in the ILS vs. NS condition resulted in block exit velocities that were significantly slower for the ILS condition by 0.45 m/s (p<0.01), a difference of 14.5% relative to the mean of both conditions.

Mean Force, Time, and Impulse Data for Step 1 & Total Trial Time

The direction of the between-condition differences in both contact or push time on the ground and delta velocity on Step 1 were opposite those on Step 0, or the block push. Step times were longer in the ILS condition vs. NS although not significantly so (p=0.053). However, the change in velocity during the step (1.23 vs. 1.06 m·s⁻¹) was significantly greater for ILS than NS (1.23 vs. 1.06 m·s⁻¹, p<0.01) in part because the average force mean was larger for ILS vs. NS although not significantly so (0.56 vs. 0.52).

The respective durations of the aerial times between the block push and Step 1 appear in Figure 6 (left panel). However, the step times (T_{c-Step-0} + T_{air}) were significantly shorter for the ILS vs. NS condition (p<0.01). The total five-meter trial time was significantly shorter for the NS vs. the ILS condition. The absolute difference between means of 0.071 s corresponded to a 5.4% difference versus the overall mean time from both conditions of 1.332 s.
Discussion

We posed a basic curiosity question in our title here that was piqued by the outcome of earlier work (chapter 3) that identified the benefit of initiating maximal legged accelerations by pushing with both legs simultaneously. Specifically, we wondered why sprinters would stagger the position of their feet to separate the pushes of right and left legs in time, when pushing simultaneously and accelerating more rapidly from sprint starting blocks is clearly possible. Moreover, the benefit of doing so is substantial, accelerations 1.5 times greater than those of the best sprinters in the world were made possible by the dual leg push from inline positions for the diving exercise we examined previously. Clearly, if sprint runners could accelerate at rates 1.5 times greater than existing norms, this would be significantly advantageous. However, this outcome would also fly in the face of conventional wisdom and prevailing the practice of staggered foot stance starts. Accordingly, we hypothesized the need to land a first running step that is removed by the dive condition must somehow disallow accelerations equivalently rapid for running. Our specific expectations were the ILS condition starts for running would have the following drawbacks: a more vertical push orientation and take-off, a prolongation of the aerial time after block exit, and compromised force application on the ensuing step. Our data proved each of these hypotheses to be incorrect. Rather, we found that the large block forces we observed during inline dives were halved when runners exited the blocks from the same inline position to run. The ILS force vs. time profiles here (Figure 2) closely matched those previously observed for the inline dives; they were simply reduced by half (chapter 3, Figure 5, bottom row). Given how consistent per limb acceleration forces have been across conditions, forces that were halved, but had the same time pattern strongly imply that our subjects pushed with only one
limb in the ILS running condition. This appears to be the basic modification participants made when required to place a lead limb down for an ensuing running step.

*Mean Force, Time, Impulse and Angle Data: Step 0*

Our ensemble averaged waveforms (Figure 3) illustrate the similarity of the average vertical and horizontal forces over the duration of the block push in the NS and ILS running conditions examined here. Because of the overall similarity in the magnitude and pattern of force across the conditions, the force vector representations of the respective block pushes appearing in Figure 4 are virtually identical. In both cases our participants applied force at angles above 45° that agreed to within 0.1°. This result refuted our first hypothesis of a more vertically oriented push in the ILS vs. NS condition.

Direct comparisons of the condition-specific group averages for the mean horizontal forces and times (Figure 5, upper and middle left column panels) for the Step 0 push in the blocks revealed a statistical difference for time, but not for the average horizontal force. We had anticipated that time would likely be shorter for the ILS vs. NS conditions because this was the case for the dives executed from the same starting positions (chapter 3). With all other factors being held equal, greater force application and acceleration would result in greater forward bodily displacement and therefore full extension of the pushing limbs taking place in less time. In the present comparison, the forces did not differ resulting in similar forward displacements per unit time – a result that is consistent with force being applied largely by a single limb only in the ILS condition. This result is also consistent with the pattern observed from staggered stances. Typically, force application occurs almost exclusively with the back leg initially, and
subsequently by the front leg only with relatively modest overlap (Henry, 1934; Slawinski et al., 2012; Willwacher et al., 2016).

The impulses and corresponding changes in velocity observed for step zero (Figure 5, lower left panel) were significantly greater for the NS vs. ILS almost entirely because the time of force application was longer. Our participants left the blocks with a velocity nearly 16% faster in the NS vs. ILS condition (3.33 vs. 2.88 m/s, respectively). These results for the ILS start are in good agreement with earlier observations and conclusions regarding the drawbacks of bunched starts. As with earlier comparisons between intermediate and bunched block pedal positions, our ILS condition also resulted in reduced force application times, reduced block exit velocities, and slower times to 5 meters (Henry, 1934; Sigerseth & Grinaker, 1962; Slawinski et al., 2012). In this regard, our results add support to the existing consensus regarding the basis for the disadvantages of bunch starts reported in the literature (Bezodis et al., 2019; Harland & Steele, 1997; Henry, 1934; Slawinski et al., 2012).

Aerial Times, Force and Impulse Data: Step 1

Per Figure 5, the aerial times between Step 0 and Step 1 also did not differ across the two-foot placement conditions. The respective means for NS and ILS conditions for this variable also were nearly identical (0.067 vs. 0.065 s). Given the nearly identical block push angles and force magnitudes when exiting the blocks, equivalence in aerial times is not surprising. However, our incorrect a priori expectation of greater and more vertically oriented block pushes led us to hypothesize to the contrary. These results lead us to reject our second hypothesis that ILS aerial times between Step 0 and Step 1 would be greater than in the NS condition.
Our third and final hypothesis was that force application during Step 1 would be impaired in the ILS vs. NS condition. As can be seen in the panels on the right hand column of Figure 5, both the times of force application and the mean horizontal force applied in the ILS condition were moderately, but not significantly greater for the ILS vs. NS condition. However, the change of velocity that resulted from the product of the magnitude and time of force application was significantly greater for the ILS vs. NS condition. These results lead us to also reject our third hypothesis that that Step 1 force application would be less forceful and impulsive in the ILS vs. NS condition.

Although unexpected, our step 1 results, particularly in the broader context of the current data set, do have a likely supporting explanation established in the literature. As Rabita and colleagues have noted, the mean horizontal forces athletes can apply during accelerated sprinting decrease on a step-to-step basis and do so in a highly linear fashion (Rabita et al., 2015). The simplest conceptualization of the phenomenon is that the primary consequence of faster horizontal speeds being attained over successive steps is a progressive, step-by-step reduction of the time available to apply force over the same steps. Reductions in total contact time take place at the direct expense of that fraction of the contact time when the body position is anterior to the foot as needed for the limb to apply force backward (i.e. horizontally). In the present condition comparisons, the slower velocity of the body after Step 0 in the ILS vs. NS condition enabled our participants to apply greater horizontal forces, simply because they were traveling slower and had more time in the position needed to do so. Consequently, the change in velocity on step 1 was greater during Step 1 in the ILS vs NS condition. The slower center of mass velocity when exiting the blocks, in this regard, provided a force application advantage, rather than disadvantage that had been hypothesized.
Functionally, the observed velocity differential also had a second unforeseen effect, the large across-condition velocity difference upon exiting the block push of 0.45 m·s⁻¹, was progressively reduced over the remainder of the 5-meter sprint. Illustrating this, the between-condition velocity differential for the full trial of 0.22 m·s⁻¹ (3.86 vs. 3.66 m·s⁻¹, for NS and ILS, respectively) was less than half that present upon block exit. Clearly, our subjects progressively closed the large across-condition post-block velocity gap over the subsequent steps in the trial. In this regard, poor starts offer a mechanical silver lining – the slower block starts in the ILS condition providing mechanical conditions that enabled relatively greater accelerations on the subsequent steps.

*Why do sprint athletes stagger their pedals?*

If we directly return to the question of why sprint athletes stagger their feet and block pedals, often at intermediate distances, our data provide a relatively clear answer. This practice allows the full force of the back leg to be provided over an early initial portion of the block push and the full force of the front leg to be provided over the latter portion. Consequently, our participants were able to apply a stance-averaged horizontal force of 1.0 F_{wb} and accelerate at a rate of 9.81 m·s⁻² for longer durations from the staggered starting position. One question our results do not answer, however, is why many of the world’s best sprinters use starting positions with relatively short between-pedal distances (Figure 1). Clearly, most of the pedal distances we could acquire from world-class sprinters are placed at distances less the intermediate zone the literature recommends. A second related question raised is why the pedal distances selected are so variable. Among our subjects, between pedal distances spanned nearly a four-fold range from 15 to 56 cm - a range that corresponds to 40% of the leg length of our subject’s legs from the hip
axis of rotation to the ground. This is a remarkably large difference for human runners of similar body sizes performing the same brief, and well-defined motor task. A portion of the variability observed undoubtedly lies in the differing dynamic force capabilities that are critical for sprint acceleration performance. However, a portion may also be explained by our observation that the best block starts appear to compromise the acceleration that takes place on subsequent steps and vice-versa. This may embed an intrinsic trade-off into the shorter and longer pedal choices athletes make to explain the large variability observed.
References


Author Contributions

LCB: conceptualization, data collection, data analysis, figure preparation, writing, and editing.

SW: data collection and editing.

PGW: conceptualization, data collection, data analysis, writing, and editing.

All authors have reviewed and approved the manuscript and are accountable for its content.

Conflict of Interest

The authors declare no competing interests.

Funding

This research was funded by a Fairess Simmons Doctoral Fellowship to LCB and the Glenn Simmons Endowment to PGW.

Acknowledgments

We extend our gratitude to Sunil Prajapati for timely assistance in figure preparation and to Rae Edwards, Darryl Woodson, and Jon McDowell for their significant help with subject recruitment.
Figure Captions

**Figure 1.** Illustrations of the set and block exit positions for the two foot-placement conditions: normal sprint start position (NS, top) and inline sprint start position (bottom, ILS).

**Figure 2.** Between-pedal block spacing distances for the original subjects tested here, the world championship male 100-meter finalists from the 2013 World Championship in Moscow, and the additional male sprinters who were among either among the top seven all-time performers at the shortest standard sprint distance of 60 meters (n=2), or who finished first at the World Championships (1987 and 2017) and were known to be exceptionally fast starters (n=2).

**Figure 3.** Ensemble averaged force vs. time patterns for the horizontal component (left panel) and vertical component of the block force pushes in the normal foot placement (NS, blue waveforms), and inline foot placement positions (ILS, red waveforms), respectively. Both horizontal and vertical force components of the push were more variable across time for NS vs. ISLS and the push time was significantly longer.

**Figure 4.** Mean block push magnitudes and angles in the two sprint start foot-placement conditions (blue arrow, NS; black arrow, ILS). Plotting the magnitude of horizontal component of the push (X-axis) vs. the vertical component of the push (Y-axis) provides the push angles. For references, block pushes for two dive conditions from the same starting block positions are also provided by the gray arrows. The larger force magnitude vector with the more horizontal orientation represents the inline dive condition, the smaller magnitude vector with the more vertically oriented vector represents the dive from the normal sprint foot placement position.
**Figure 5.** Mean push or contact times (top panels), the average horizontal forces applied (middle panels), and the change in center of mass velocity (bottom panels) on both the push out of the blocks (Step 0, left column panels), and the first step after exiting the blocks (Step 1, right column panels) for both foot-placement starting conditions, normal start (NS), and inline start (ILS). Statistically significant differences between the two conditions are identified with the asterisks (*).

**Figure 6.** Mean time in the air between Step 0 and Step 1 ($T_{air}$, left panel), total Step 0 time ($T_{step-zero}$, center panel), and total five-meter times ($(T_{5-meter}$, right panel) for both foot-placement starting conditions, normal start (NS), and inline start (ILS). Statistically significant differences between the two conditions are identified with the asterisks (*).
Figures

Figure 1

Normal Start (NS)

In-Line Start (ILS)

Figure 2

Consensus from literature

Black Spacing (cm)

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Figure 3

![Graph showing $F_y$ and $F_z$ forces with time (m·s⁻¹)].

Figure 4

![Graph showing relationship between vertical and horizontal components (BW)].
Figure 5

**Step 0**
- Time\_pierh (s)
- Force\_avg (W/kg)
- ΔVelocity\_com (m/s)

**Step 1**
- Time\_pierh (s)
- Force\_avg (W/kg)
- ΔVelocity\_com (m/s)

Legend:
- NS
- ILS

* indicates statistical significance.
Figure 6
Conclusion

Gravity as the Limit

We first hypothesized that the best runners are limited to an acceleration of 1 G during the block start. This hypothesis stems from the fundamental constraints of gravitational forces and the need for dynamic balance during acceleration. Our investigations, supported by previous research, confirmed that the gravitational support force and balance requirements indeed limit sprint accelerations to this upper threshold of 1 G. The findings were consistent across both bipedal and quadrupedal runners, with quadrupeds operating closer to this theoretical limit than humans. Studies on greyhounds and other fast quadrupeds provided additional support, illustrating that multiple limbs allow for more continuous force application and reduced aerial periods between steps, thus enhancing acceleration capabilities. Despite confirming the 1 G limit, we sought to understand if there were conditions under which runners could push harder. The theoretical framework suggested that while peak horizontal forces might momentarily exceed 1 G, maintaining such force application consistently without compromising balance and introducing prolonged aerial periods is not feasible. Our findings underline that this gravitational limit is a practical ceiling for sustained sprint accelerations.

Force Application without Constraints

In our second study, we hypothesized that removing constraints that hinder force application would lead to greater bodily accelerations through increased push-off forces. We assumed that eliminating mechanical constraints, such as minimum push angles and the need to avoid excessive aerial time, would enhance force application. Our experiments compared normal sprint starts with maximal-effort dives, revealing that while peak horizontal forces did not significantly
differ, the average horizontal forces were greater in dive conditions. This increase was attributed to the prolonged rear-leg push duration, which enhanced force application. Consequently, acceleration forces were maximized, given the time available for force application. These results highlight that maximizing acceleration is not merely about applying greater forces but optimizing the duration of the force application. The rear-leg push duration emerged as a critical factor, underscoring the importance of timing in sprint mechanics.

*The Need for Staggered Starts*

The final study examined the impact of starting positions, testing the hypothesis that two-leg pushes would increase force application during the sprint start. This assumption was based on the idea that simultaneous leg pushes could generate greater initial force. To address this, we compared typical staggered stance starting positions to starts with feet in line. Contrary to our hypothesis, the findings revealed that two-leg pushes hindered the time of force application, resulting in a slower start. Staggering the legs allowed sprinters to prolong the block push-off time, optimizing body and limb positioning and highlighting the importance of staggering the feet during the sprint start to achieve optimal push times for acceleration performance.

*Final Thoughts*

These findings underscore the value of exploring the limits of human locomotor performance, offering insights that benefit a variety of fields. Understanding these mechanics can enhance training, improve designs, and guide practices across diverse contexts. This research contributes to a broader comprehension of movement and force application, highlighting the potential for advancements in multiple disciplines.