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NEUROMUSCULAR RESPONSES TO EXHAUSTIVE BOUTS OF SPRINT RUNNING IN NON-STEADY SPEED TRIALS

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By

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Chapter 1: Review of Relevant Literature and Study Introduction

Musculoskeletal Performance Decrements

With increments in the duration of exhaustive exercise, individuals experience decrements in the performance intensity that can be attained. Decrements in performance that occur during bouts lasting from a few seconds to approximately 5 minutes are exponential, with the most rapid performance decrements occurring in efforts lasting less than 60 seconds (1). In contrast, during bouts lasting greater than 5 minutes performance loss is much less rapid, and similar levels of muscular force and power output can be maintained for events lasting as long as several hours (2, 3). For shorter duration efforts the rate and magnitude of an individual's performance loss can be predicted to within 2 percent using individual specific performance-duration relationships if three variables are known (4). The first variable is the greatest musculoskeletal performance that can be achieved by the individual and typically can be sustained for three or fewer seconds. The second variable is the greatest performance that can be supported primarily by aerobic metabolism, i.e. the velocity at VO_2 max (4). The final variable is an exponential time constant describing the rate of decay over the range of non-sustainable performances (4). The exponential constant varies by mode but works universally for all subjects (5,6).

Force Application and Human Running Speed

Human runners change speed by altering the amount of force they apply against the running surface. Further, it is the application of vertical ground reaction forces that is the most important factor in attaining high sprinting speed (7, 8, 9). Somewhat counterintuitively, the vertical ground reaction forces exceed those in the horizontal direction by roughly 10-fold during constant velocity running (6, 10). Thus to maintain a particular running speed, the body must employ similar levels of force application throughout the effort (10). These observations give rise to the general relationship that an increase of one meter per second of forward speed is achieved by augmenting ground force application by 10% of the runner's bodyweight (11).

Neural Control of Force Production

Descending motor drive from the central nervous system (CNS) regulates how much force muscles apply against the external environment, and how quickly that force is exerted. Action potential delivery from increased efferent drive increase force output by recruiting greater numbers of motor units, or by increasing the frequency of action potential delivery (12). The recruited motor units are comprised of many muscle fibers and a single α-motor neuron, which is excited by descending action potentials from the CNS (13). These motor units are successively recruited based on Henneman's size principle as force demands increase, with the smallest units being recruited at the lowest recruitment threshold (12). Force output from skeletal muscle can also be achieved through increased motor unit discharge rates; this increased rate coding results in greater force through the summation of multiple muscle twitches (14). The motor units with the largest fibers and highest force production capability also require the greatest discharge rates and exhibit the greatest range of discharge rates (15). These recruitment patterns and the degree of muscular activity can be measured using surface electromyography, as EMG measures the electrical voltage changes occurring during depolarization of the nerve axon and the muscle cell sarcolemma (16).

Thus, increased force output is characterized by a linear increase in the EMG signal (16, 17), as increased force output requires greater muscular involvement and therefore greater stimulation from the CNS. Typically, increased EMG signal strength is attributed to increased recruitment, as the voltage from the action potential of each motor unit is additive (17). Furthermore, in trials where fatigue is not present EMG signal strength increases linearly as force increases, with the highest force outputs yielding the most significant EMG signals (9).

Neurophysiology of Fatigue

Fatigue is commonly defined in the scientific literature as a reduction in the force or power production capability of skeletal muscle (18). While many common motor tasks are undeniably difficult to sustain, most popular activities do not meet this definition of fatigue because these tasks do not require continuation until failure occurs. Moreover, most commonly performed modes of activity require relatively constant levels of muscular force output. For example, constant velocity sprint running requires similar levels of force production throughout a bout (10), but task failure can easily be achieved in less than ten seconds. These realities necessitate a different approach to the quantification fatigue. Surface EMG detect altered levels of neuromuscular activity, and are useful in the assessment of fatigue during constant force contractions. During constant force muscle contractions, the presence of fatigue can then be measured by progressive increases in EMG (19) a phenomenon referred to as compensatory neuromuscular activity.

The classical expectation for the onset of muscular fatigue and the associated neuromuscular responses is that these processes were driven by the absolute level of muscular force applied (20). Recent work demonstrates that varying neuromuscular responses occur at identical levels force output. These results indicate when efforts rely more heavily on anaerobic metabolism neuromuscular compensation is triggered as is the onset of fatigue (19). The onset of neuromuscular compensation, and the time course to fatigue are dependent on the extent to which there is a reliance on anaerobic metabolism (19), with greater use of anaerobic metabolic pathways resulting in more rapid failure of active motor units, causing neuromuscular compensation to maintain task performance by recruiting additional muscle fibers (21). The presence of neuromuscular compensation during constant force exercise can be interpreted as increased CNS drive resulting in the recruitment of additional motor units to aid the fatiguing units already enlisted in the exercise bout (22, 23).

Compensatory neuromuscular activity is triggered during exercise when ATP demands cannot be fully supported by aerobic pathways, and additional energy must be provided through the phosphagen and glycolytic ATP pathways (9, 24, 25). The aerobic system of human runners can sustain forces that are 75-85% of those experienced during a top speed sprint, typically equating to stance average forces that are twice the subject's body weight (9). If these force requirements cannot be met primarily through aerobic respiration, anaerobic mechanisms of ATP resynthesis are used and the intensity is unsustainable and the onset of force impairment is triggered (4, 25). The exercise intensities that rely most heavily on anaerobic metabolism experience the most rapid rates of performance loss and the greatest degree of neuromuscular compensation (9, 21). In these situations, EMG increases continually until the failure point of the exercise bout (9). In contrast, compensatory activity does not occur at exercise intensities that can be supported primarily by aerobic metabolism and can be sustained for considerable durations (9, 21). During these longer, sustainable efforts, EMG signals are essentially constant, indicating a constant volume of active muscle fibers (9).

Pacing during Exhaustive Exercise

When humans complete tasks with sufficient force requirements to necessitate a reliance on anaerobic metabolism fatigue develops and we observe a progressive impairment of the muscle's ability to produce force (9). During these demanding tasks humans often vary their exercise intensity to preserve adequate force production capacity to complete the task and to optimize their performance (26). Three commonly employed and scientifically explored pacing strategies are possible: fast-to-slow, slow-to-fast and even pacing. Even pacing is a strategy where the participant maintains a constant velocity throughout the entire event. Fast-to-slow pacing is characterized by a fast start with decreasing velocity throughout the bout, and slow-to-fast pacing employs a relatively slow start, and velocity is increased throughout the event (26). Empirical support documenting the validity of these strategies is almost entirely absent from the literature. Simulation models of various pacing strategies suggest that short duration efforts of less than 80-100 seconds are optimized by a fast start and reduction in speed as the participant becomes fatigued throughout the event (27). Energy flow Models simulating track cycling indicate that in exhaustive events lasting longer than 2 minutes, even pacing where a consistent speed is maintained throughout the event is ideal (28). Energy flow model based predictions are supported by analysis of track & field world records in the 800, 5000 and 10000-meter disciplines, which suggest that a fast-to-slow pacing strategy was used in all but two 800m world record performances from 1912-1997, and even pacing strategies have been used in all 5000 and 10000 meter world record performances from 1921-2004 (26). In contrast, slow-to-fast pacing where speed increases throughout the event seems to be used mainly in disciplines like speed skating and sprint cycling where an acceleration phase is thought to be an important component of the event (29).

Goals of the Current Study

In the current project the effects of fast-to-slow, slow-to-fast and even pacing strategies were investigated on sprint running performances lasting from 3-300 seconds.

Previous works have used modeling (28), or post-hoc analysis from world record performances (30) to infer appropriate strategies for various event durations. However, a valid physiological explanation or rigorous scientific evaluation of these preliminary ideas is absent from the literature to date. Accordingly, an experimental design was developed that administered a single speed change of 15% at the midpoint of exhaustive sprint trials and measured the resulting descending motor drive patterns. Cumulative distance obtained was compared in the trials involving either a midpoint increment or a midpoint decrement vs. the steady speed condition and evaluated the onset and extent of fatigue development during these efforts. The resulting data permitted the evaluation of the effectiveness of the various pacing strategies and to determine whether fatigue development is influenced by the level of muscular activity immediately preceding an involuntary change in intensity.

Chapter 2: Introduction

Goals of the Current Study

The present study aims to quantify the effects of fast-to-slow, slow-to-fast and even pacing strategies during sprint running. Previous works have used models which simulated race performance (28), or gathered empirical evidence from lap times of from world record track performances (30) to suggest appropriate applications for various pacing strategies. Other published works on the topic have studied the effectiveness of pacing strategy in cycling and kayaking (31, 32, 33, 34), but little work has been directed at fully understanding the performance outcomes of pacing during sprint running. The current study aims to provide empirical evidence demonstrating which pacing strategies most effectively optimize run performance over a range of efforts 3-240 seconds in duration.

The goal of the present study was to determine how a change in running speed midway through an exhaustive sprint running trial affects the duration for which the effort can be maintained. Trials of similar duration in each of the three experimental conditions was compared to determine at which durations fast-to-slow, slow-to-fast and even pacing optimize performance.

Hypothesis

It was hypothesized that there would be no difference in distance completed between any slow-to-fast, even or fast-to-slow pacing strategy in trials of similar duration lasting less than 80 seconds. It was also hypothesized that distance completed in efforts longer than 80s but less than 240s would also be unchanged by pacing strategy during trials of similar duration.

Significance of Current Project

The present study will extend the current understanding how fast-to-slow, slow-to-fast or even pacing can influence sprint-running performance. Previous research has investigated similar pacing strategies in cycling, kayaking and other modalities but the existing pacing literature involving running focuses almost exclusively on long duration exercise bouts. The focus on sprint running durations of less than 240 seconds is a novel aspect to this project.

Rationale for Current Project

The present study is necessary in order to further understand the role pacing plays in helping humans prolong task execution, or optimizing sprint running performance during exhaustive durations of 3-240 seconds. No current research has assessed the effectiveness of pacing strategies over the entire range of non-sustainable sprint performances.

Delimitations

This project used college aged males who regularly engaged in recreational running. College aged males were used primarily as a convenience sample, since that population is accessible at the research laboratory. Running was used as the test modality as a continuation of a series of research by this lab investigating non-sustainable sprint running performance. Sprint running is also of personal interest to the researcher.

The range of performances used (3-240s) was used because these are the range of performances that have been shown to be highly predictable in the rate of performance decrement in previous research. The predictable decrement of constant speed performances over this range allowed for reliable comparison to non-steady speed trials.

Another notable choice from the research team is the use of a single speed change during non-steady efforts during this study. The choice for a single speed change minimized the risk of failed transitions during the speed change, as some subjects struggled to smoothly transition when speed demands instantaneously changed. The single change of pace also allowed for more manageable analysis, as each change of speed had to be manually identified by the researcher. The 15% magnitude of pace change used was the largest pace change that subjects could consistently complete without failure at the point of pace change.

Limitations

Varying subject groups could have been used for this project. Female subjects, competitive runners, or a population of different age could all be next steps to advance from the starting point established here. Similar research could also be completed at durations above 240s. Longer durations were intentionally omitted from this project as those efforts likely rely on different physiological fatigue mechanisms and may be optimized by different effort distribution strategies.

The use of a single speed change was carefully considered by the research team. Real-world scenarios where pacing strategies are employed generally have constant fluctuations in effort and therefore speed and force. The use of either multiple changes of speed, or continual changes in speed were not used both because it is not possible to continually change speed on the treadmill, and because the analysis of EMG results would not be meaningful without periods of constant force during the exhaustive efforts.

Applied Outcomes of this Research:

It is currently unknown whether pacing strategy can alter performance in exhaustive sprint runs of 3-240 seconds in duration. The current study may clarify whether pacing can alter sprint running performance in efforts lasting less than 240 seconds and may provide insight into what strategies are most effective over this range. Outcomes of this project could potentially be used to develop strategies for run performance over the tested range. It was hypothesized that there would be no difference in distance completed between any slow-to-fast, even or fast-to-slow pacing strategy in trials of similar duration lasting less than 80 seconds. It was also hypothesized that distance completed in efforts longer than 80s but less than 240s would also be unchanged by pacing strategy during trials of similar duration.

Chapter 3: Methods

Experimental Design

An experimental design was developed that included a series of exhaustive sprint runs using three different pacing strategies, even, fast-to-slow and slow-to-fast. The protocol began with a series of ten constant velocity exhaustive sprints that comprised the even pacing condition of the study. The runs covered a wide range of speeds with durations ranging from 3-300 seconds. Data from the constant velocity trials were used to accurately predict the duration any performance between maximal aerobic speed and maximal anaerobic speed could be maintained. To test the hypotheses that shorter trials (<80s) and longer trials (>80 and <240s) would be unchanged by pacing strategy, a series of twenty non-steady exhaustive trials were conducted. Half of the non-steady trials employed a fast start pacing strategy and spanned the full range of non-sustainable performances previously discussed. The remaining half of the non-steady trials employed a slow-to-fast pacing strategy and also spanned a wide range of non-sustainable performances. Subjects were unaware whether the upcoming speed change would represent an increment or decrement in the sprinting speed.

For all trials, distance traveled was calculated, enabling a direct comparison between the non-steady conditions and the constant velocity baseline trials. The calculation of distance completed provided an objective basis to evaluate the most successful pacing strategy across the entire time window of interest, i.e. the greatest distance covered in the same time period. Trials where the distance covered was less than in the constant velocity trials indicated reduced performance and an ineffective strategy for that duration.

Materials and Methods

Subjects. Six male (Mass = 78.04 ± 6.12 kg) subjects volunteered and provided their written informed consent to participate in this study, which was preapproved by the University of Montana's institutional review board. All subjects indicated that they engaged in recreational running at least three days per week and were in good health.

Experimental Protocol. A sprint running protocol that employed both constant velocity and non-steady sprint running trials was used to test the hypothesis that sprint performances of durations less than 300 seconds would not be optimized by varying pacing strategies. A range of sprint running strategies were tested, including constant velocity, fast-to-slow and slow-to-fast paced trials on a customized high-speed force treadmill.

Figure 1. *Testing Protocol*

Session 1	VO_2 max test
Session 2	5 constant velocity exhaustive runs
Session 3	5 constant velocity exhaustive runs
Session 4	Maximal running speed test
Session 5	5 non-steady exhaustive runs
Session 6	5 non-steady exhaustive runs
Session 7	5 non-steady exhaustive runs
Session 8	5 non-steady exhaustive runs

Subjects completed two experimental conditions, which required a minimum of eight laboratory visits. Subjects completed the testing sessions as follows: subjects performed a preliminary session using a progressive, discontinuous treadmill test to determine running speed at VO_2 max. Sessions two and three each began with a standardized five-minute warm-up at 2.5 m/s, after which the subject completed a set of five randomized constant velocity sprints at varying speeds, eliciting failure between 3 and 300 s. During these sessions, subjects took a minimum of fifteen minutes rest between each exhaustive bout but were allowed to take as much rest as necessary to feel fully recovered. During session four an incremental treadmill test was administered to discern the maximal running speed the subject could attain for eight consecutive steps. The subject started with a five-minute warm-up running at 2.5 m/s, and was given as much time as is necessary to feel fully rested between trials. Sessions five through eight employed a randomized set of five non-steady exhaustive sprints that elicited failure between 3 and 300 s. A change in running speed equivalent to 15 percent of the speed administered in the first half of the trial, with 10 of these trials involved an increase in speed, and 10 trials were administered with a decrease in speed at the half-way point based on the duration expected for a constant velocity trial.

Maximal Aerobic Speed. The greatest speed which each subject could support through aerobic metabolism was determined by a progressive, speed-incremented, discontinuous treadmill test consisting of 5-minute bouts of constant-speed running subjects were permitted as much rest as they deemed necessary to be fully recovered typically these were three to six-minutes during the initial trials and approached 15 min as the intensity approached the aerobic limit. The initial speed was 2.5 m/s and subsequent trials increased in speed by .3-.5 m/s until a speed was reached where the subject could not complete the full five-minute bout. During minutes four and five of each bout, expired air volumes were analyzed for fractions of oxygen and carbon dioxide, rates of Oxygen uptake, are presented as STPD. The maximum speed supported by aerobic metabolism was calculated from the highest single minute VO_2 value measured and the linear relationship between VO_2 and speed for each individual. A minimum of six steady state values less than 90% of VO_2 peak were used to formulate individual VO_2-speed relationships (4).

Sprinting Decrements. Treadmill trials began with the subject lowering himself from the handrails onto the treadmill belt moving at the desired speed. Subjects were instructed to put forth a maximal effort and continued until they could not maintain their position on the treadmill. If a subject drifted backward more than 20cm from their initial position on the treadmill, that was considered trial failure. Upon failure, subjects were instructed to grab the handrails and straddle the treadmill belt until it stopped. Subjects wore a safety harness for all trials, as a counter measure in case of a fall. Each subject completed eleven all-out trials over a range of speeds eliciting failure between 3 and 300s in duration. Typically, the longest exhaustive trial was the final bout administered during the maximal aerobic speed test.

Each subject's speed-duration relationship was determined in accordance with:

Eq. 1

where t is the duration of the exhaustive run, Spd(t) is that speed maintained for a run of duration t, Spd_{ts} is the subject's top speed, Spd_{aer} is the maximum speed supported by aerobic power, e is the base of the natural logarithm, and k is the exponent that describes the decrements in speed that occur with increments in run duration. Each subject's speed-duration relationship was used to determine the expected durations for the administration of the non-steady speed trials and distances achieved in the even pacing condition.

Top Speed. Each subject's maximal running speed was determined from the greatest speed he could maintain for eight consecutive footfalls without backward drift on the treadmill (10). The test consisted of a series of short sprints at progressive speeds until the subject could no longer maintain his position on the treadmill without backward drift (20cm) for eight consecutive steps. Subjects initiated each trial as previously described and were given as much time as needed to feel fully recovered between each run.

Non-Steady All-Out Treadmill Runs. Subjects completed twenty non-steady speed exhaustive runs over the course of four laboratory sessions. One subject completed only nine trials due to recurring muscle soreness. During each run a change of pace was administered once the subject completed 50% of the duration expected for an effort of the initial speed. Half of the trials started quickly and involved a decrease in speed half way through the bout equivalent to 15% of the starting speed, and the remaining ten trials started slowly and increased in speed by 15% of the initial speed. Subjects were informed that the change would occur and were given a 5 second countdown to the change but were blinded to the direction of the speed change. Subjects were instructed to continue running until they could no longer maintain their position on the treadmill. Subjects were required to take a minimum of fifteen minutes of rest between each trial.

Treadmill Force Data. All force data were collected using a custom high-speed force treadmill (35). The force data were amplified (AMTI, MSA-6; MA, USA) and digitized (Axon Instruments Inc., Digidata 1322A; CA, USA) at 2000 Hz. Data from each trialwere collected at 2000hz and filtered for analysis (WaveMetrics Inc., Igor Pro 6.34A; OR, USA) using a dual pass of a 6-pole, low pass, butterworth filter with a cutoff frequency of 40 Hz. Treadmill force values from each trial represent the average vertical forces from a series of at least eight consecutive footfalls. Average force was defined as the mean vertical ground reaction force recorded over a .005 second interval during the last 80% of the foot-ground contact period (4). Peak forces are expressed as multiples of the subject's bodyweight.

Electromyography. Bipolar surface EMG electrodes were placed on the skin of the right leg, over the muscle bellies of the vastus medialis, vastus lateralis, medial gastrocnemius and lateral gastrocnemius with an interelectrode distance of .025m. The reference electrode was placed on the anterior aspect of the iliac crest. Consistent electrode placement during each data collection session was achieved by marking each electrode site with indelible ink during the subject's first and subsequent laboratory visits. Subject was instructed to reapply the ink as necessary throughout their participation in the study. To minimize electrical impedance, the participant's skin was shaved, lightly abraded, and cleaned with alcohol prior to electrode application. If the inter-electrode impedance exceeded 3000 Ω, the electrodes were removed, and the skin was cleaned with alcohol, prior to reapplication of new electrodes. Surface EMG signals were amplified (x500) and filtered (3-3000 Hz half-amplitude band pass and 60Hz notch filter) using four amplifiers (P511; Grass-Telefactor, Warwick RI). Analog outputs from the amplifiers were digitized at 3003 Hz and recorded throughout the duration of each running trial by a computer using an A/D convertor. Electromyography data were rectified and integrated on a per contraction basis (iEMG).

Analysis & Statistics. All data were analyzed using custom computer software and algorithms (WaveMetrics Inc., Igor Pro 6.34A; OR, USA). Data were reported as means +/- SD. Data from our two experimental conditions was tested for significance using a paired samples t-test. The level of significance for the statistical tests will be set at $P < .05$ *a priori* .

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Chapter 4: Results

Subjects: Six male subjects completed the study. The average age of the subject pool was ___. The average body mass of participants was 78.04 ± 6.12 kg.

Maximum Aerobic Power: The study mean maximum aerobic power was 62.0 ± 4.2 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$ (range = 54.7 - 68.1 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$). Aerobic metabolism supported speeds at VO_2max of 4.8 ± 0.5 m/s (range = 4.0 - 5.5 m/s). The speed at VO_2max was determined from the relationship of VO_2 vs running speed obtained during the discontinuous test to VO_2max, these regressions yielded a mean R^2 value of 0.98 ± 0.02 (range= 0.95 - 0.99).

Top Speed: The mean top speed was 8.4 ± 0.4 m/s (range = 7.9-9.1 m/s). The mean non-susrange of non-sustainable speeds (the difference between top speed and the speed at VO_2max) was 3.7 ± 0.6 m/s (range = 2.6-4.4 m/s; Fig. 1).

Ground Force Application: Stance average ground force application increased with running speed (Fig 1) and was 1.39± 0.09 xBW during the 2.5 m/s standardized warm up and reached 2.14± 0.13 xBW during the trials administered to determine top speed. The range of 1.39-2.14 xBW represented a range of stance forces of 574N (1063N to1636N) for the typical subject. The regression of stance average force on running speed was $F_{avg} = 0.11 \bullet Speed + 1.21$ with a mean $R^2 = 0.81 \pm 0.14$. Thus, the 15% speed change altered ground force application by 0.08 xBW (64N) in the sprints closest to the velocity at the aerobic maximum, and by 0.14 xBW (110N) in the trials closest to the subject's top speeds.

Sprint Trials: Of the total 172 exhaustive trials administered in this study, 66 were constant velocity sprints and 106 trials included the unannounced velocity change. The subjects completed an average of 29 exhaustive running trials each throughout their participation.

Sprinting Decrements: The measured decrements in running speed experienced with increments in trial duration (Fig. 2) were well predicted by Eq. 1 yielding an $R^2 = 0.98 \pm .01$ (range = 0.96 - 0.99), using the measured parameters and the mean k value 0.019

(range = 0.015 - 0.027) obtained from this group of subjects. The high predictive accuracy of these individual relationships (Fig. 3) produced a study standard error of estimate of 0.24 m/s and an average absolute difference between the measured and predicted performances of 2.99%.

Performance Response to a Speed Change: The effectiveness of trials with a slow-to-fast *vs* a fast-to-slow speed change was assessed by comparing the total distance covered for each administered trial [i.e. $Distance = (Speed_1 \bullet Duration_1) + (Speed_2 \bullet Duration_2)$], to the distance expected for a trial of the measured duration using an even pacing strategy in accordance with Eq. 1 (Fig. 4 & 5). Due to the vagaries of random assignment, 57 trials were slow-to-fast, of these, 39 trials achieved a distance less than expected by even pacing (i.e. Eq. 1), and 18 trials surpassed this expectation. Of the 49 trials administered from fast-to-slow, 17 of these did not achieve the distance expected by even pacing, whereas 32 trials surpassed this expectation. Among the slow-to-fast trials those that did not achieve the level expected by even pacing completed a distance that was -2.7 ± 1.8% less than anticipated. The trials exceeding the predicted, did so by +2.4± 1.7%. The overall effectiveness of the slow-to-fast trials compared to even pacing was -1.1 ±3.0%. Among the 17 fast-to-slow trials that did not achieve the even pacing distance, these were -1.6 ± 1.2% less than anticipated. The trials exceeding the predicted did so by +2.8± 1.4%. The advantage of the fast-to-slow trials compared to even pacing was +1.3 ± 2.7%. In summary, the effectiveness of slow-to-fast pacing (-1.1±3.0%) was statistically ($\rho<0.001$) less than that of the fast-to-slow strategy (+1.3 ± 2.7%).

Electromyography: A custom developed algorithm was used to detect and analyze the periods of muscle activity from the four instrumented muscles (Fig. 6). To date 107 832 individual muscle contractions recorded during this study have been analyzed using this algorithm. The contraction-by-contraction EMG data revealed the following: during the steady-state sustainable efforts, iEMG typically decreased during the first 30 s of a trial and subsequently remained constant. During the steady speed sprints to failure, 42 series (i.e. an individual muscle's response throughout a trial) were either constant or experienced a negative relationship between iEMG and trial duration, in contrast 43 series exhibited progressive increases in neuromuscular activity (Fig. 7). In the non-steady speed trials four responses in the iEMG records were possible, the slopes of iEMG regressed on trial duration could have been, positive and positive, positive and negative, negative and positive or negative and negative, for the first and second portions of the trials respectively. 312 regressions were comducted to determine the iEMG response, in each muscle and during each portion of the non-steady speed trials for the 156 iEMG responses analyzed. Similarly to the constant velocity exhaustive sprints, during the first portion of the non-steady speed trials 51.9% (n=81) contained increasing values of iEMG, and 48.1% (n=75) of the iEMG records were either constant or decreased. Results were consistent regardless of the speed transition administered, specifically 56.0% of the iEMG records from the slow-to-fast trials (n=84) exhibited the increasing iEMG response whereas, 47.2% of the iEMG from the fast-to-slow trials included an incrementing measure.

In contrast to the equivocal response measured during the steady-speed trials and the first portion of the non-steady speed trials, 78.2% of the iEMG records obtained during the second half of the non-steady speed trials exhibited the increasing iEMG response (122 of 156 records).

Table 1. Physiological and performance characteristics of the subject group.

Subject #	Speed @ VO_2 Max (m/s)	VO_2 Max (ml/kg/min)	Top Speed (m/s)	K-Value	R^2 for curve fit
1	4.4	59.7	8.4	.0153	.986
2	5.5	68.1	8.1	.0208	.997
3	5.1	63.6	9.1	.0255	.981
4	5.0	61.4	8.6	.0188	.984
5	4.6	64.9	7.9	.0195	.994
6	4.0	54.7	8.4	.0171	.983
Mean:	**4.8**	**62.1**	**8.4**	**.0195**	**.988**
Std Dev:	**0.539**	**4.628**	**.42**	**.0035**	**.006**

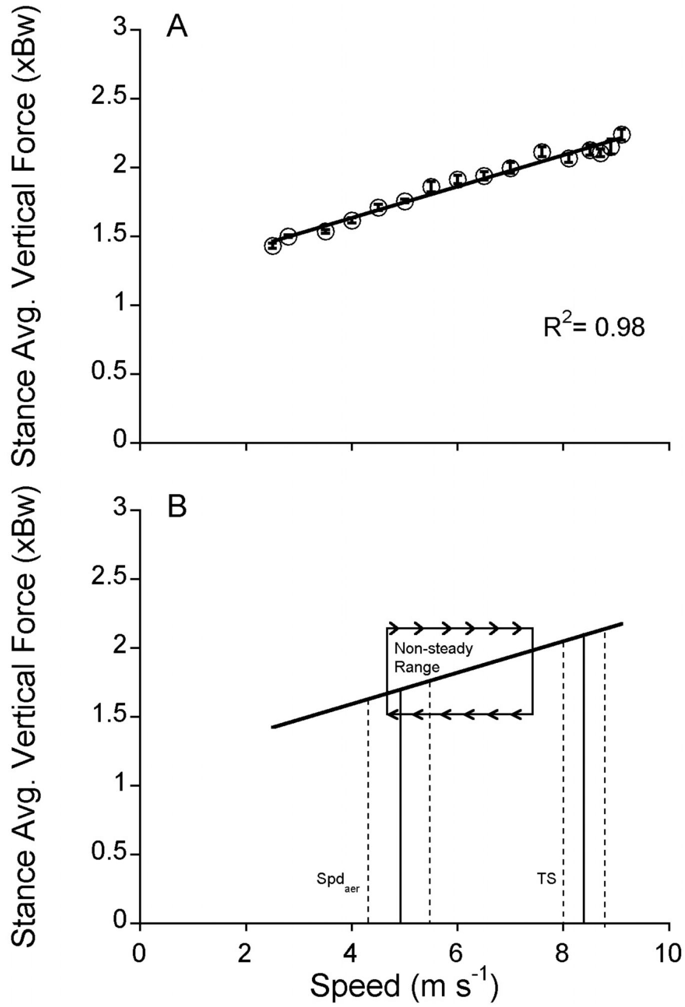

Figure 1: (A) Stance average forces from a typical subject across the entire range of running speeds. B) Study mean values for stance average force, Spd_{aer}, and top speed (TS), dashed lines indicate one SD. The region highlighted by the box indicates the typical range of speeds used for the non-steady speeds. At the faster range non-steady speeds could not be administered if the 15% increment would exceed an individual's top speed.

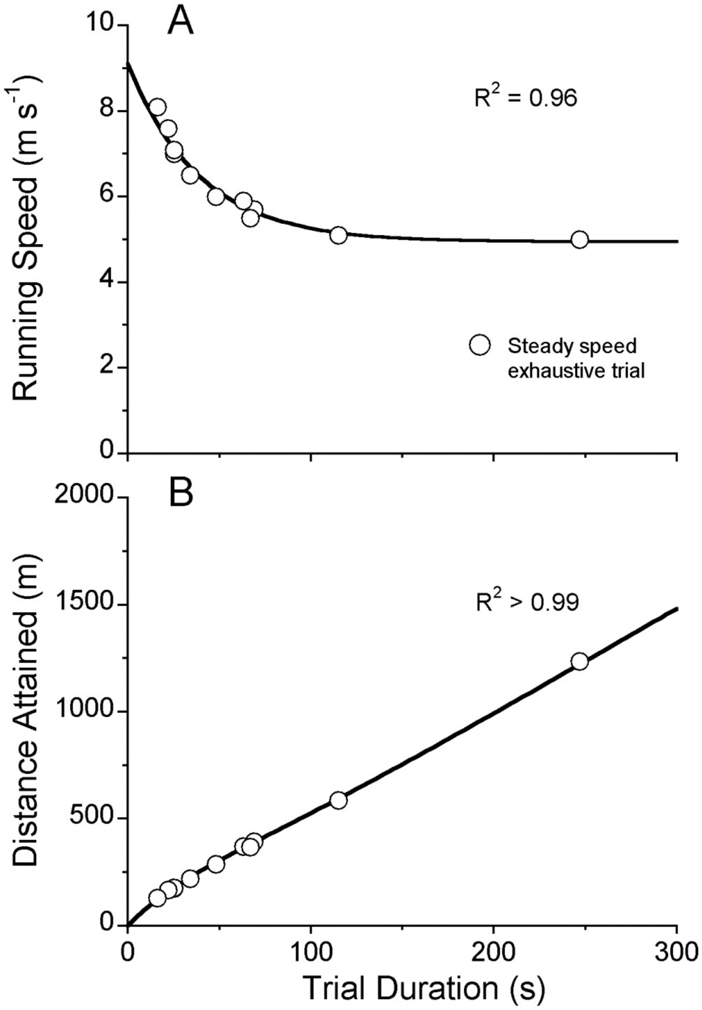

Figure 2: (A) Individual sprint duration relationships were well predicted by EQ 1, here expressed relative to speed (A) and distance (B), for a representative subject completing steady-speed sprints. The relationship from B was used as the basis to evaluate the effectiveness of the non-steady speed conditions.

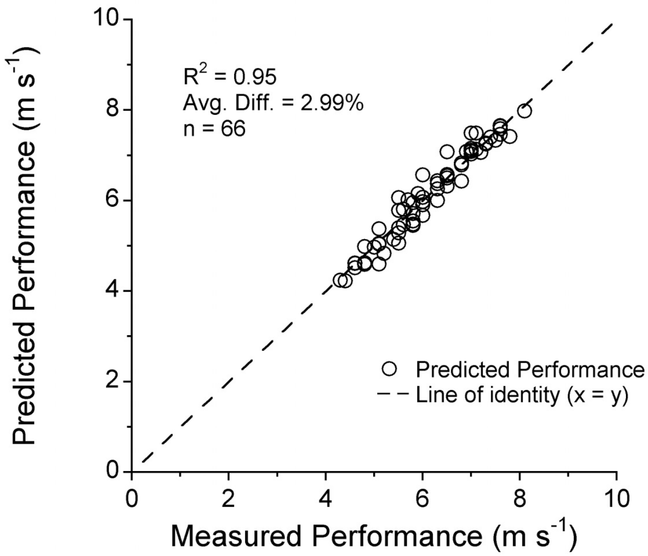

Figure 3: The measured vs predicted performances had high agreement with the line of identity (i.e. x=y) indicating the ability to accurately quantify individual efforts of durations less than roughly 300 s.

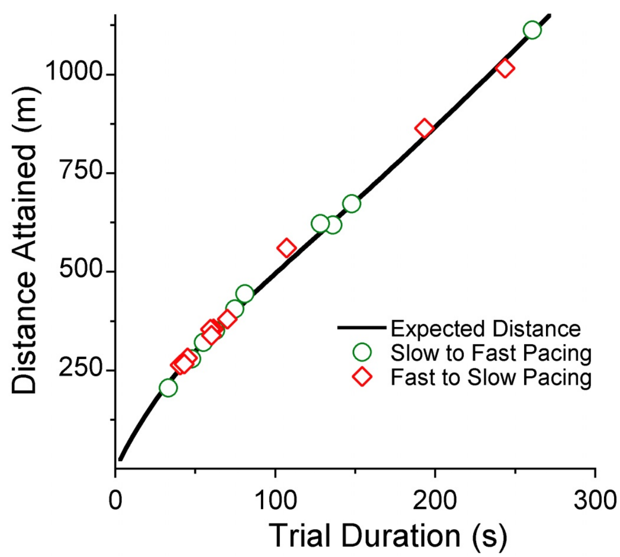

Figure 4: Measured (symbols) vs expected (solid line) distances for the slow-to-fast and fast-to-slow pacing conditions for a typical subject.

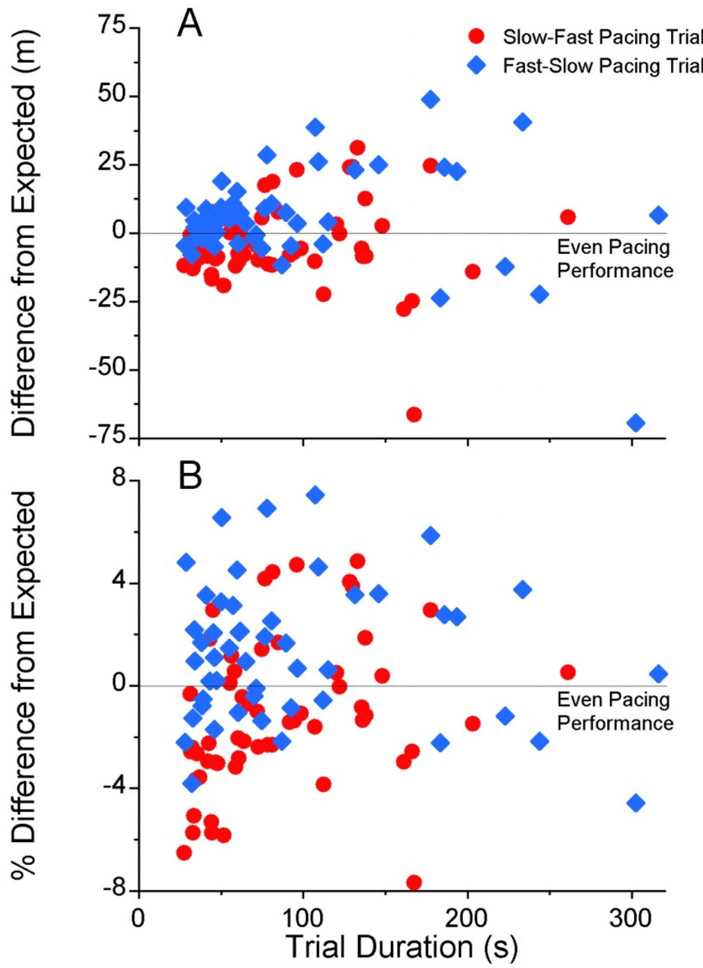

Figure 5: (A) Measured distances for the slow-to fast and fast-to-slow trials administered in this study (n = 106) expressed in absolute (A) and relative (B) increments from the steady-speed measures obtained from each subject.

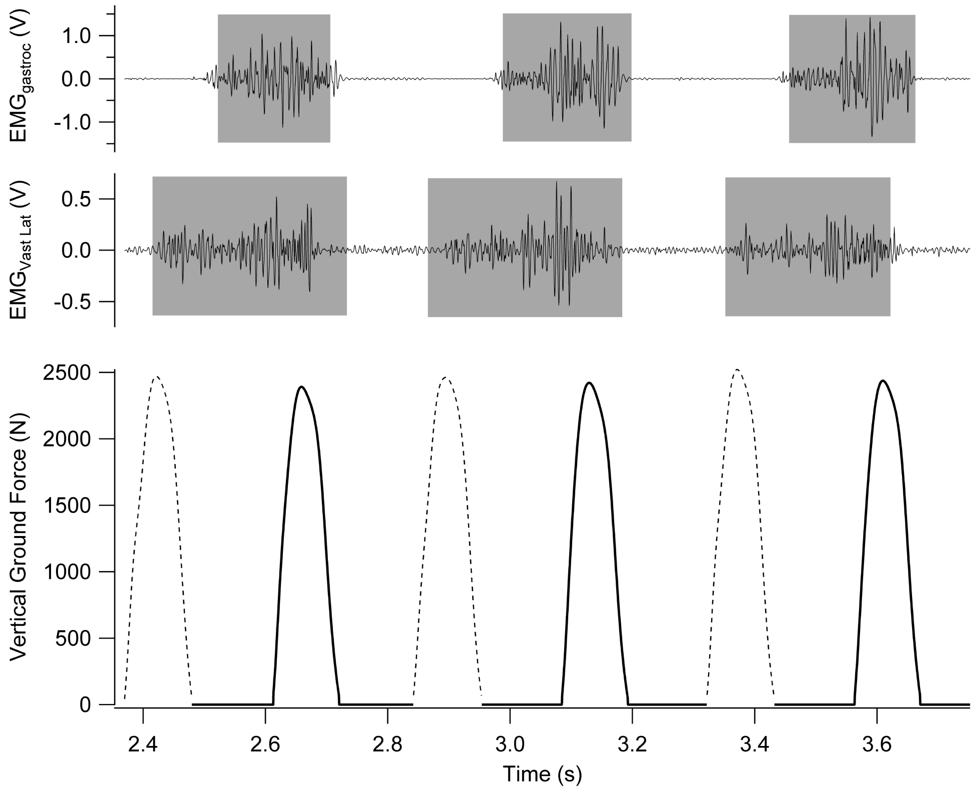

Figure 6: Raw EMG recordings from the *Gastrocnemius*(A) and *Vastus Lateralis* (B) and vertical ground reaction forces (C) during a representative trial. Shaded boxes in A & B represent the area of EMG integration identified by the custom algorithm for subsequent integration and analysis. Dashed footfalls in C are the contralateral, non-instrumented limb

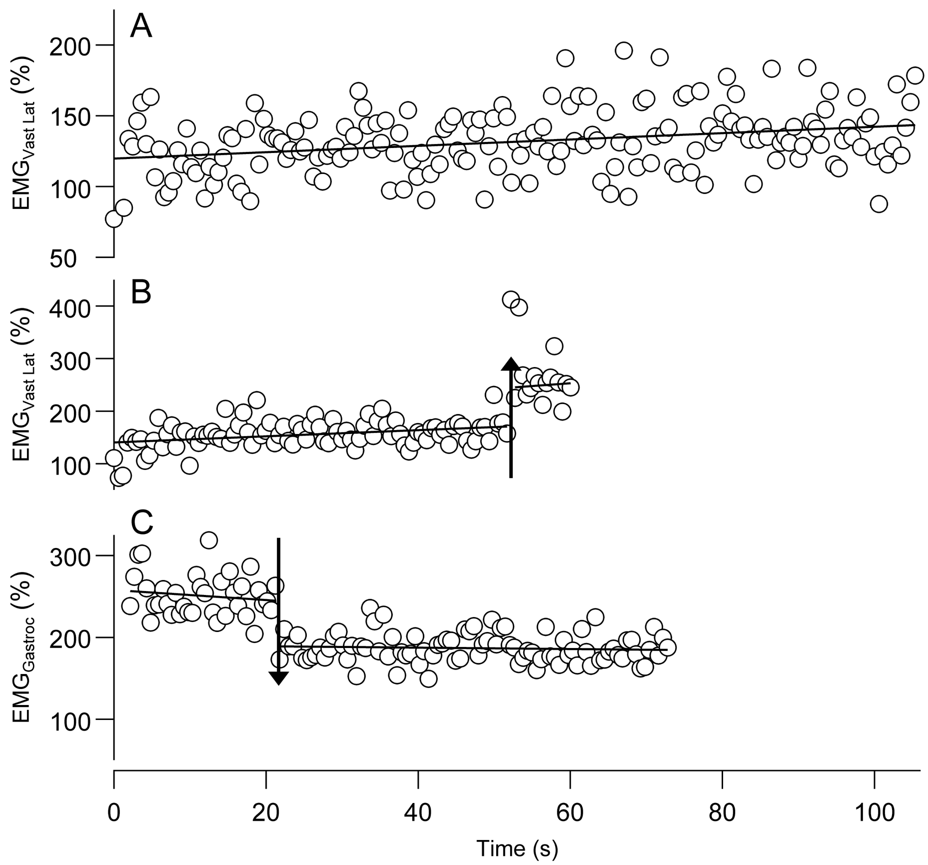

Figure 7: (A) Integrated, step-by-step EMG values during a constant speed sprint trial (A), a slow to fast speed trial (B) and a fast to slow trial (C). Arrows in B & C indicate the moment of speed change. EMG values are expressed relative to a standardized warm-up conducted at the beginning of each laboratory session.

Chapter 5: Discussion

The current project investigated the effects of fast-to-slow, slow-to-fast and even pacing strategies on sprint running performances lasting from 3-300 sec. A single speed change of 15% was administered at the midpoint of 20 exhaustive sprint trials each subject completed, the alteration in running speed similarly altered the required ground force application to run at the second speed by 0.08 xBW (i.e. 64N) in the sprints closest to the velocity at the aerobic maximum, and by 0.14 xBW (i.e. 110N) in the trials closest to the subject's top speeds. The cumulative distance obtained in each trial was compared to the steady speed condition and the effectiveness of slow-to-fast pacing (-1.1±3.0%) was found to be statistically ($\rho<0.001$) less than that of the fast-to-slow strategy (+1.3 ± 2.7%). When evaluated across the range of exhaustive durations obtained in this study (27-316 s) the effectiveness of the slow-to-fast strategy improved in longer vs shorter trials (Fig. 5). For instance, when the effectiveness of the pacing strategy was evaluated for the 51 slow to fast trials which reached a failure in less than 150s the influence of exhaustive duration on distance reached, resulted in a positive relation ($R^2 = 0.26$). In contrast, the trials with the administered fast to slow speed transition were essentially equally effective across the durations obtained ($R^2 = 0.01$).

Sprinting Performance During Constant Pace Efforts

Constant speed sprint running performances are highly reliable over the entire range of non-sustainable performance durations (Fig. 2) and the decrements experienced in short vs long efforts follow a similar time course between individuals (4). Thus, absolute performance for any particular duration depends on the magnitude of the velocities supported by each individual's aerobic limit and their top sprint speed, with similar relative rates of loss between these levels for all subjects (4). In regard to the prediction of constant speed running performance, results are consistent with established findings of the high predictability of these decrements and provided agreement between measured performances and those predicted based on trials of equivalent duration (Eq. 1) to be within 3.0% (Fig. 3). Although, the study mean value for the exponential constant was somewhat greater than found in previous work (i.e. 0.019 vs 0.014 [4]) which have found exponential constants that are, on average, greater than the .019 found in the current study. Nonetheless, the consistency of each individual's speed-duration relationship provided an experimental foundation upon which to evaluate the effectiveness of the two pacing strategies.

Performance Response to a Speed Change:

The existing literature on experimental undertakings documenting the physiology and potential performance benefits of pacing strategies is limited. Studies using several modes of locomotion exist, these efforts have either evaluated the performances of individual athletes during the course of world best efforts (30), generated predictive models using expectations that have not been evaluated experimentally (28), or assessed the potential of altered strategy over single specific distances or within a very limited (i.e. 6 sec) range of durations (34). In contrast, data collected during this project was obtained across the entire range of non-sustainable durations and the possible sprint speeds during both steady speed and altered speed sprinting provide first of its kind experimental data to evaluate the effectiveness of these interventions. Performance was evaluated with respect to the cumulative distances achieved during steady speed sprint running. The highly predictable nature of the steady-speed running relationship permitted the mathematical integration of the speed-duration curve to produce a distance-duration relationship (Fig 2B), that was specific to each individual performer and valid across a temporal window representing the entirety of the non-sustainable performance range. These individual relationships provided an empirical and objective basis from which to evaluate the effectiveness of the slow-to-fast or fast-to-slow pacing strategies. Further, because the subjects were blinded to the directionality of the speed change we likely removed any anticipatory aspects of effort regulation which may be present during longer sustainable bouts of exercise (37).

The experimental design used here permited the evaluation of the superiority of different pacing strategies across the range of exhaustive durations, rather than at discrete instances within the time window. The interaction of metabolic energy availability which is the primary performance determinant for the relatively longer sprint efforts, and the mechanical and gait-related factors that determine speed for the briefest possible durations might have imposed different pacing strategies for improved performance across this range of durations. In contrast, linear regressions of the relationships between the extent of the performance change either as absolute distance (Fig 5A) or the relative change as a percentage of the expected distance (Fig 5B) vs exhaustive duration were not significant in 3 of the 4 comparisons. The weakly descriptive regression equation (R^2 = 0.09) quantifying the relationship between the fraction of the expected distance (Fig 5B) vs trial duration in trials with a slow to fast speed change ($\rho = 0.03$) indicates that these trials averaged distances that were typically 2.1% less than those of the steady speed condition for the shortest durations (i.e. 27.2 s) and were 2.9% further than steady speed sprinting at the longest conditions (i.e. 316.2 s). However, the apparent temporal improvement in the slow to fast trial distances with increments in the duration of the exhaustive trials was due to the reduction in the disadvantage imposed by this speed change, rather than a trend towards superior performances. Specifically, of the 57 trials administered with this speed change only 18 trials improved upon the expected steady-state distance, with only 2 of these trials occurring beyond the 152 s mark representing the transition from disadvantage to advantage as indicated by the least squares equation. Thus, for efforts without an initial acceleration phase, as the case here, our results indicate that the fast to slow condition more consistently augments the distances attained than trials that were either of the slow to fast type or those that were steady speed.

Neuromuscular Response to Altered Ground Force Requirements and Fatigue

The percentage-based alteration in speed that were administered resulted in changes to the level of applied ground force necessary to maintain the speed in the second half of each trial (Fig. 1B). As a result, the muscular contribution required during these trials was also altered and observed as either an increment or decrement in the electromyogram (Fig. 7). The increased EMG activity during constant-load exercise is most commonly attributed to altered motor unit recruitment to adjust the level of activated fibers (2, 17, 36) used to generate muscle force. Altered motor unit discharge rates may also be responsible for the increased EMG activity but are not likely the primary factor, in the large muscle bellies of the leg (1, 17, 28, 29). These conclusions are determined primarily from studies on isometric contractions due to the inherent difficulty of tracking individual motor unit action potentials during dynamic contractions. Irrespective of the precise motor control strategy, the altered EMG activity following the change in sprint speed provided an opportunity to observe subsequent changes in motor drive in trials where the rate of neuromuscular fatigue was either incremented or decremented.

However, the results of this portion of the experimental undertaking were mixed. In previous work with other modes of exhaustive exercise progressive increases in EMG activity have been nearly universally observed (e.g. seen in 454 of 474 exhaustive trials, [21]), and indicate compensatory neuromuscular recruitment to overcome impaired muscle force production and maintain performance. However, during both the steady-speed exhaustive trials and the first portion of the non-steady speed trials administered here, roughly half of the EMG measures were constant or decreased slightly. Although following the alteration in speed the neuromuscular response more consistently (78% of trials) conformed to previous results and expectation and exhibited compensatory neuromuscular activity.

The equivocal EMG results from the steady-speed and first half of the non-steady speed trials are fully unexpected and are difficult to explain in the absence of similar contraction-by-contraction measures (Fig 6) from the literature. Among the possibilities are; 1) unlike the more controlled modes of exercise such as knee extension and cycle ergometry where performance is maintained only by muscular contributions, sprint running speeds might be sustained by a combination of gait related adjustments in addition to the muscular contribution. A more thorough analysis of the ground force data can be used to evaluate this possibility and reveal kinematic adjustments, temporal alterations to critical stride parameters and potential within trial changes in force application. 2) The rates of performance decrement and the onset of muscular fatigue in sprint running may be sufficiently low that neuromuscular compensation is difficult to observe. Yet, this phenomenon was observed in a mode of exercise with performance decrements occurring roughly half as rapidly as those measured here with exponential time constants of 0.011 vs 0.019 respectively (21). 3) The neuromuscular response to fatigue may differ on the basis of contraction type. Previous work in this area has used modes of exercise relying on concentric contractions, however during running muscle sarcomere length is virtually isometric, and joint excursions are made possible by flexible tendons (38). However, classical work on the motor control of muscle fatigue universally used isometric contractions sustained until failure to document compensatory activity (39). Although it is unclear whether these findings occur in intermittent isometric contractions similar to those observed during spring running. Additional analysis of this data and future experimental work can be used to evaluate the validity of these explanations.

Concluding Remarks

The current project investigated, for the first time the effect of manipulating pacing strategy over a full range of non-sustainable sprint running durations. It can be concluded that such interventions can indeed affect sprint performance and the duration for which a wide range of sprint performances can be sustained, with fast to slow pacing consistently outperforming slow to fast or constant speed strategies. The magnitude of performance differences between the fast-to-slow and slow-to-fast strategies was large enough to make noteworthy differences in race outcomes. In an elite men's mile race the difference between fast-to-slow and slow-to-fast pacing would make the difference of 5.76 seconds, equating to the fast-to-slow paced athlete winning by roughly 38 meters. In an elite men's 400m race the difference between strategies was 1.05 seconds equating to the fast-to-slow paced athlete opening a 9.5-meter gap on the slow-to-fast paced runner. The performance differences described are the difference between 1st and 22nd place in the most recent NCAA 1500m semifinal race, and the difference between first and 12th in the 400m semifinal.

The neuromuscular response of constant or depressed EMG activity observed during the first segment of the non-steady bouts and constant speed exhaustive runs was an interesting divergence from the expected response of neuromuscular compensation throughout the sprint trials. The results were unexpected and may create interest in future examination into what parameters contribute to this unexpected neuromuscular response during sprint running.

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