Relationships Between Neuromuscular Capacity and Distance Running Performance in a Sample of College Athletes

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Abstract

The purpose of the current study was to explore the relationship of strength and muscle power factors (400m time, 30m time, countermovement jump (CMJ) height, modified reactive strength index (mRSI), peak force (PF), rate of force development at 0 - 150 ms (RFD150), 2K time trial time) with distance running performance (season best 1500m time and highest International Amateur Athletic Federation (IAAF) score). Ten healthy, female NCAA DII distance runners performed the following tests over two days: (1) CMJ, 30m sprint, 400m sprint; (2) isometric mid-thigh pull (IMTP), 2K time trial. The variables measured were: CMJ height and mRSI, 30m time, 400m time, PF, RFD150, 2K time. The season best 1500m time and overall best performance converted into IAAF score were recorded for each athlete at the conclusion of the season. Pearson correlations of the variables with 1500m time showed 400m time to have the highest correlation (r = 0.90, p < 0.005), followed by 2K time (r = 0.72, p < 0.5), RFD (r =-0.65, p < 0.05) and 30m time (r = 0.65, p < 0.05). Similar results were observed for highest IAAF score. Relative importance analyses of the multiple regression models showed 400m time to be the most important variable for both 1500m time (*LMG* = 0.34) and highest IAAF score (*LMG* = 0.36); and RFD150, 30m time and 2K had statistically equal relative importance. In conclusion, among a homogenous group of distance runners, 400m time and the ability to sprint and generate force quickly might be important predictors of race performance.

Introduction

Superior performance in distance running (foot races of 800m to 10,000m) can be attributed to complex interactions of physiological, biomechanical, environmental and psychological factors. When it comes to the physiology of endurance running, most research has been focused on the aerobic metabolism. The three primary physiological factors contributing to endurance performance are maximal oxygen uptake (VO_2max), running economy (RE), and lactate threshold (LT) (Joyner & Coyle, 2008; McLaughlin et al., 2010; Lanferdini et al., 2020; Kipp et al., 2019). Additional indicators of endurance performance include velocity at maximal oxygen uptake (vVO_2max), anaerobic function (velocity during maximum anaerobic test or vMART) and neuromuscular capacity (Beattie et al., 2014).

Maximal oxygen uptake, or VO_2max refers to the amount of oxygen that an individual can utilize during intense exercise (Bassett & Howley, 2000). VO_2max can be expressed as an absolute value, in liters/minute, or as a relative value (ml/kg/min), indicating the amount of oxygen in milliliters that the body can use for each kg of body weight per minute (Bassett & Howley, 2000).). VO_2max is a good predictor of endurance performance when it comes it heterogeneous populations, but highly trained runners often have very similar VO_2max values (Kipp et al., 2019). Thus, other physiological factors such as lactate threshold (LT) and running economy (RE) can influence endurance performance (Kipp et al., 2019).

Lactate threshold is defined as the point at which lactate starts to accumulate substantially above resting values during long term aerobic exercise (Joyner & Coyle, 2008). Lactate threshold identifies the percent of VO_2max that can be maintained for a prolonged time during endurance exercise (McLaughlin et al., 2010). An athlete with a higher lactate threshold value can maintain a given submaximal intensity without rapid accumulation of lactate in the blood (Baldwin et al., 2021). Consequently, when comparing the aerobic capacity of two endurance athletes with similar VO_2max values, the one with the higher lactate threshold generally outperforms the one with a lower lactate threshold.

Running economy refers to the energy demand required at a given velocity, and it is often measured as the amount of oxygen in milliliters consumed per kilogram of body mass that is needed to run a kilometer (Shaw, Ingham & Folland, 2014). Running economy tends to be a better predictor of endurance performance than VO_2max when it comes to homogenous populations of elite endurance runners (Conley & Krahenbuhl, 1980). In fact, variability in running economy between elite endurance athletes can be as high as 20-30% (Noakes, Myburgh &Schall, 1990) and up to 65% of variation in competition performance might be attributed to differences in running economy (Conley & Krahenbuhl, 1980). Higher RE values mean that an athlete can ran at a faster speed for a given rate of oxygen consumption, leading to superior performance (Joyner, 1991).

Velocity at VO_2max (vVO_2max) is the running speed at the last completed stage during a maximal incremental running test at which VO_2max is reached (Lanferdini et al., 2020). Velocity at VO_2max is highly dependent on VO_2max and running economy (McLaughlin et al., 2010), as over 80% of the variance in vVO_2max can be explained by these two elements (Lanferdini et al., 2020). When looking at predictors of a 16K time trial performance, McLaughlin et al. (2010) found that vVO_2max accounted for 94.4% of the total variance 16K time, similar to the findings of Noakes et al. (1990) on the performance predictors of elite long distance runners. Velocity at maximal oxygen uptake is one of the strongest physiological predictors of endurance performance, as it incorporates both aerobic power and running economy (Beattie et al., 2017; McLaughlin et al., 2010).

It has been proposed that besides the aerobic and anaerobic capacity of an athlete, neuromuscular capacities also play a role in endurance performance (Beattie et al.,2014).

Neuromuscular characteristics affect running economy and certain muscle power factors such as anaerobic function (vMART), therefore partially determining the value of vVO_2max (Beattie et al., 2014, 2017).

When it comes to highly trained runners, improving key predictors of endurance performance such as running economy might be hard to obtain (Beattie et al., 2017). For this reason, identifying new training modalities that can result in any degree of improvement in performance can be key for success. Furthermore, better understanding the relationship of physiological variables and running performance can help both coaches and athletes in determining the most beneficial types of supplemental training to include in addition to their regular endurance training.

As opposed to the role of the aerobic and anaerobic power and capacity, there is not much literature available on the role of neuromuscular capacity in determining endurance performance. Despite the growing number of studies focusing on strength interventions for distance runners (Beattie et al., 2014, 2017; Berryman et al., 2010; Mikkola et al., 2007) and other endurance athletes (Baldwin et al., 2021), there is more research needed to understand the relationship of neuromuscular capacity and endurance running performance.

Review of Literature

Based on current literature, the main physiological factors explaining individual differences in endurance performance are maximal oxygen uptake (VO_2max), running economy (RE) and lactate threshold (LT) (Joyner & Coyle 2008, di Prampero et al. 1986). Traditional training programs tend to focus on improving these key parameters of aerobic fitness, through implementing submaximal endurance training and high intensity interval training workouts (Midgley et al., 2006).

However, not all the variance in endurance running performance can be explained by the state of the runner's aerobic metabolism. Previous research suggests that beyond aerobic and anaerobic power and capacity, neuromuscular capacity (muscle power factors) also contribute to endurance performance (Beattie et al., 2017). As opposed to the aerobic components of endurance performance, neuromuscular characteristics and their contribution to distance running performance are less well studied.

Examples of neuromuscular characteristics include force-producing ability, maximal speed and muscle power (Blagrove et al., 2018). Some of the most common tests for assessing neuromuscular capacity, muscle power and strength variables include the maximal anaerobic running test (MART) (Paavolainen et al., 1999), different jump tests to assess lower leg power such as countermovement jump test, squat jump, drop jump, 3-jump test or 5-bound jump test (Beattie et al., 2014; Hudgins et al., 2013; Spurrs et al., 2003), 20m or 30m maximal sprint (Beattie et al., 2014; Blagrove et al., 2018; Paavolainen et al., 1999) as well as tests to evaluate isometric force of lower body muscles (1RM) and rate of force development (Spurrs et al., 2003).

The maximal anaerobic running test (MART) is an endurance specific muscle power test (Beattie et al., 2014). The most commonly assessed outcome variable during this test is peak velocity (vMART). The MART consists of a series of incremental 20 second runs separated by

100 second recovery periods on a treadmill, performed until exhaustion (Beattie et al., 2014). Since during MART athletes have to produce power while glycolytic energy production and muscle acidity is high and muscle contractility might be limited, vMART is a good measure for evaluating muscle power (Blagrove et al., 2018). According to Nummela et al. (2006) and Paavolainen et al. (1999), two important factors determining vMART are the capacity of the neuromuscular system to quickly repeatedly produce force and anaerobic power. There is a positive correlation between vMART and running times for distances ranging from 400m to 5000m (Paavolainen et al., 1999). Moreover, research suggests that there is a strong relationship ($r = 0.85$) between vVO_2max and vMART (Paavolainen et al., 2000).

A countermovement jump (CMJ) is a vertical jump performed without an arm swing, and is commonly used to evaluate explosive qualities of the leg muscles in athletes (Young et al., 2011). Jump height from a CMJ test is a measure to evaluate lower leg power (Li et al., 2019). The CMJ can also be used to assess the modified reactive strength index (mRSI), an important indicator for endurance performance (Beattie et al., 2017). Reactive strength measures the force producing capacity of the muscle-tendon complex during the concentric contraction that immediately follows a rapid eccentric contraction (Li et al., 2019). Similar measurements can be obtained from the drop jump test, which is a maximal vertical jump performed immediately following a drop from a 30 cm high box (Beattie et al., 2017). The main difference between CMJ and drop jump tests is that the CMJ assesses the slow stretch-shortening cycle (SSC) function while the drop jump assesses the fast SSC function, both of which are categories of reactive strength movements (Beattie et al., 2017).

As opposed to the CMJ and drop jump test, the 3-jump and 5-bound jump tests measure jump distance, not height. The 3-jump test measures the distance covered in three two-leg standing long jumps which are performed in immediate succession, and is used to evaluate lower leg horizontal power (Hudgins et al., 2013). The 5-bound distance test (5BT) measures the horizontal distance covered during a series of five forward jumps performed with alternate legs (Spurrs et al., 2003). Similar to the vertical jump test described above, the 5BT can indicate the function of the SSC of the muscles of the legs (Spurrs et al., 2003).

The 20 or 30m maximal sprint tests can be used to evaluate maximal sprinting velocity (V_{20m} or V_{30m}) (Blagrove et al., 2017). Measuring maximal sprinting velocity is relevant to distance runners because races often involve sprint finishes (Blagrove et al., 2017). Additionally, through increasing their maximum speed runners can lower their relative work-rate, leading to a decrease in anaerobic energy contribution (Blagrove et al., 2017). Lastly, a study by Nummela et al. (2006) found that there is a relationship between 20m sprint velocity and vMART in a sample of well-trained male distance runners (10,000m time under 38 minutes), suggesting that vMART is partially dependent on maximal running velocity.

Rate of force development (RFD) is a measure of explosive strength calculated from the time spent and the work distance during lifting while performing a squat expressed in watts (Storen et al., 2018). In their study investigating the effects of maximal strength training on running economy in a sample of well-trained distance runners (male and female, VO_2max above 56 ml/kg/min), Storen et al. (2008) found a significant correlation between RFD and RE values pre-intervention, suggesting a relationship between RFD in the muscles that are active during running and RE. Rate of force development can also be measured using isometric mid-thigh pull testing (IMTP), which has been reported to be a safer and more time efficient method traditional 1-repetion max (1RM) testing (DeWitt et al., 2018). Both 1RM and IMPT can be used to evaluate maximal strength qualities (such as peak force, maximal strength). Improving maximal strength can help distance runners as there is a positive correlation between maximal strength and reactive strength levels in athletes, which are suggested to be the most important strength quality for distance runners (Beattie et al., 2017).

Most of the literature on neuromuscular capacity and muscle power factors is composed of strength intervention studies, as one way to improve neuromuscular factors is through the implementation of strength training (Beattie et al., 2017). Recent research has been focused on different modalities of strength training, added to the regular training regimen of distance runners to evaluate its effect on endurance performance (Spurrs et al., 2003; Storen et al., 2008). However, studies on neuromuscular capacity and muscle power factors date back to the end of the 1990s, where Finnish researcher Paavolainen and colleagues published a series of studies investigating the components of 5K running performance (Paavolainen et al.,1999; Paavolainen, Nummela & Rusko, 1999, 2000; Paavolainen et al., 2006).

In one of their first published studies, Paavolainen et al. (1999) found that a 9-week explosive strength training intervention improved 5K time trial time in a sample of elite male cross-country runners (8+ years of experience competing), without a change in the athletes' VO_2max values. There was a strong correlation between improved 5K times and running economy, as well as vMART in the experimental group. This led the authors to the conclusion that improved neuromuscular characteristics lead to an improved vMART and RE, ultimately resulting in a faster 5K time (Paavolainen et al.,1999). In a different paper published the same year, Paavolainen et al. (1999) reported significant correlations between neuromuscular characteristics and vMART with 5 km running performance. Moreover, Paavolainen, Nummela and Rusko (2000) reported that muscle power factors such as vMART, velocity at 30m maximal sprint (V30m) and blood lactate concentrations contribute largely to peak horizontal treadmill running performance, while VO_2max plays a more key role during uphill running.

A main limitation of these studies is that they all used relatively small samples (ranging from 17 to 23 participants). Additionally, the strength intervention study was only 9 weeks long in duration, which makes it difficult to evaluate longer term adaptations and effects of strength training (Paavolainen et al., 1999).

In a more recent article, Midgley et al. (2007) addresses similar limitations for the current scientific evidence on the effectiveness of strength training interventions. In their overview of current literature on ways to enhance the physiological determinants of distance running performance, Midgley et al. (2007) emphasized that there is little research available on long-term effects of different forms of strength training on running performance. As a result, any potential long-term negative effects of strength training for runners are unclear (Midgley et al., 2007). It is also not clear which type of strength training is the most effective, and what frequency and load should be incorporated into the different phases of runners' training plan (Midegley et al., 2007).

A systematic review by Beattie et al. (2014) highlighted similar limitations, emphasizing that there is a need for research that focuses on long-term strength interventions. The authors also add that there is lack of research that uses valid strength assessments (such as squat jump, countermovement jump) (Beattie et al., 2014). Some of the main findings from their systematic review include that strength training can improve 3 km (2.7%, effect size [ES] = 0.13) (Spurs et al., 2003) and 5 km time-trial performance (3.1%) (Paavolainen et al., 1999), economy (4.0–8.1%, ES: 0.3–1.03) (Berryman et al., 2010; Mikkola et al., 2007; Paavolainen et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Storen et al., 2008), vVO_2max (1.2%, ES: 0.43–0.49) (Berryman et al., 2010; Mikkola et al., 2007), and maximum anaerobic running velocity (VMART) (3%), (Mikkola et al., 2007; Paavolainen et al., 1999). Another systematic review with a meta-analysis of controlled trials had similar conclusions, stating that strength training had a large beneficial effect on running economy when it comes to highly trained runners (Balsalobre-Fernandez et al., 2016).

Some studies focused on the effects of strength training on young runners (Mikkola et al., 2007; Blagrove et al., 2018). In the study by Mikkola et al. (2007), concurrent explosive strength and endurance training was effective in improving neuromuscular and anaerobic characteristics, despite the fact that 20% of endurance training volume was substituted by explosive strength training. Blagrove et al. (2018) found that strength training is likely to improve maximal speed and endurance performance in young runners, without unwanted changes in body composition. On the other hand, Piacentini et al. (2013) looked at the effects of strength training for master endurance runners. Their findings are in agreement with the results of other strength intervention studies. Running economy in the experimental group improved, which the authors attribute to the improved rate of force development observed in response to the strength training intervention (Piacentini et al., 2013).

Jumping ability and distance running performance has been the focus of some of the recent literature on muscle power factors. Investigating the relationship between lower leg power and distance running performance, Hudgins et al. (2013) found that performance on the 3-jump test can predict running performance in events of varying distance, not limited to sprinting in a sample of NCAA Division I track and field athletes (males and females). Even though the authors point out that the strongest correlations were seen between sprint times and jump distance, they emphasize that the correlations were also significant when it came to distance running times (Hudgins et al., 2013). Taking this into account, the contribution of muscle power to these events should not be overlooked, but considered a component for training for distance runners as well (Hudgins et al., 2013).

In a study by Balsalobre-Fernandez et al. (2014), researchers found that countermovement jump height measured prior to practice had a significant correlation with RPE values taken after training sessions throughout the season for highly competitive distance runners (personal bests in outdoor 1500m between 3:38–3:58 for men; and 4:12–4:23 min for women). Moreover, the highest and lowest jumps were measured the week of the season best and season worst competition performances, respectively (Balsalobre-Fernandez et al., 2014).

Plyometric training led to a significant increase in CMJ height, 5-bound jump distance, musculotendinous stiffness (MTS) in a sample of well-trained male distance runners (average training history of 10-years) in an investigation lead by Spurrs et al. (2003). More importantly, there was an improvement in 3K time trial time and running economy following the 6-week plyometric intervention (Spurrs et al., 2003). The authors suggest that the improvements in muscle power factors (measured by the different jumping tests) and MTS lead to an improvement in RE, ultimately resulting in a faster 3K time (Spurrs et al., 2003). Plyometric training was also effective at reducing the energy cost of running, and improved vertical jump height and 3K time of well-trained endurance runners (Berryman et al., 2010).

Despite the growing body of literature available regarding strength training for distance runners, there is still a lack of understanding regarding the exact relationship between neuromuscular characteristics and distance running performance. The majority of the available literature focuses on strength training interventions, and implies that the observed improvements in running economy occur as a result of improved neuromuscular capacities (Beattie et al., 2014; Denadai et al., 2017; Vikmoen et al., 2017). However, not many studies include correlational or regression analysis between variables related to muscle power or other measures of neuromuscular capacity. Thereby, it is hard to determine the extent of the contribution these factors play in determining endurance performance.

Gaining a better understanding of these aspects of running performance can help coaches as well as athletes when deciding what workouts to allocate time for, in addition to their regular running training to optimize their training and reach better outcomes. Additionally, improving running economy with well-trained runners is often difficult as athletes might reach a plateau. Therefore, new modalities of training that can produce marginal changes can be key for success.

The purpose of the present study is to provide a better understanding of the relationship between neuromuscular characteristics and running performance of distance runners. The current study will explore this relationship through examining correlations between rate of force development (RFD150), peak force (PF), vertical jump height (CMJ), modified reactive strength index from CMJ (mRSI), 30m sprint time, 400m sprint time, 2K run time, season best 1500m time, and highest IAAF score from individual season best performances across events ranging from 800m-5000m. In addition to the correlational analysis, multiple regression analyses and relative importance analyses will be used to determine the relative importance of the dependent variables (RFD150, PF, 30m time, 400m time, 2K time) in the predictive models for 1500m time and highest IAAF score. Another aim of the study is to participate in the athlete monitoring initiative at Point Loma Nazarene University, and provide the Coaches with insights regarding the individual strength and muscle power characteristics of each participating runner.

Based on previous research, it is hypothesized that (1) 2K time, RFD, PF, 30m sprint time, 400 maximal sprint time, CMJ height and mRSI will be at least moderately correlated to 1500m time and highest IAAF score; (2) 2K time will be the most important predictor variable for distance running performance (as measured by season best performances); (3) 400m maximal sprint time will be an another important predictor of both 1500m time and highest IAAF score; and (4) the relative importance of RFD and PF values will be the least important out of the seven variables measured.

Methods

Experimental Approach to the Problem

The present study used a cross-sectional design to investigate the relationships between certain strength and muscle power factors and distance running performance. Subjects completed all testing procedures on two separate occasions over a 7-day period, with at least 24 hours between the two testing days. The first day of testing included a countermovement jump (CMJ), a 30m maximal sprint and a 400m time trial. The second day of testing included an isometric mid-thigh pull test (IMTP) and a 2000m (2K) time trial. Additionally, race times were tracked and recorded throughout the entire track and field season of competition. The following variables were recorded and analyzed: 30m max sprint time; CMJ height and modified reactive strength index (mRSI); peak force (PF) and rate of force development (RFD150); 2K time trial time; season best 1500m race time; and season best performance based on IAAF score.

Subjects

The current study was approved by Point Loma Nazarene University Institutional Review Board under the athlete monitoring initiative, and followed the National Institutes of Health Standards for human research testing. All subjects provided informed consent prior to participation. Subjects (n=10) were required to meet the following inclusion criteria: female collegiate runners, aged between 18 and 25 years old, specializing in middle or long distance events (800m, 1500m, 3K, 3K steeplechase (SC), 5K, 10K). Participants were recruited using a convenience sample of the Point Loma Nazarene University track and field team.

Procedure

The first day of testing started with a vertical jump test, using the countermovement jump test protocol. Athletes completed a standardized warm-up procedure, including 10 full body weight squats, 30 double-legged hops and 5 vertical jumps starting at 50% effort on the first jump and finishing with a jump at 90% effort. Prior to jump testing, all participants were explained the testing procedure. Athletes completed two warm-up jumps, one at 50% and one at 75% effort. They were instructed to jump as high as possible with a countermovement, keeping their hands on the hips while jumping. They were also instructed to stand still on the force plates after landing and recovery, until it is indicated that the recording has finished. Participants were given a 30 second recovery period between the warm-up jumps and prior to the 100% effort jump. Maximal jumps were repeated 3-5 times until at least 2 maximal jumps within 2 cm of each other have been recorded. After each maximal effort, athletes were read the results of the jump and were given encouragement for the next jump. Jump height in centimeters and modified reactive strength index values for each athlete were recorded. The average of the three highest jumps in centimeters, and the average of the three best mRSI values were used for all data analyses.

After the jump testing, participants completed their usual pre-practice 15-minute warm-up prior to the time trial which included light aerobic exercise, dynamic stretching and 2 sets of 100m sprints at 75% effort. Dynamic stretches included the following: toe walks, heel walks, hamstring walks, figure-4 walks, quad walks with opposite arm-reach, front lunges, side lunges, reaching steps, lateral leg swings and front to back leg swings. Each exercise was done on the track over a 20-meter stretch, while the leg swings were done standing by a wall. Sprint testing took place on the PLNU 400m flat outdoor track. Runners started with two warm-up sprints, one at 50% and one at 75% effort. Following the warm-up, they performed three maximal 30m sprints with a running start of 20 meters to ensure a normal and maximal running gait during the 30m. Between each 30m sprint, runners were given a brief recovery time that included retuning to the start of the course, and lasted until they felt fully recovered (around 2-3 minutes). Running times were measured using two photocell gates connected to an electronic timer (Newtest Ltd.). The fastest recorded 30m running time in seconds was used for all subsequent data analysis.

Following the 30m sprint test, participants completed an additional 5-minute light aerobic warm-up to prepare for the 400m time trial. All runners started together, with a staggered start. Each participant was instructed to run as fast as possible for the whole lap, and verbal encouragement was given throughout the whole time. Times were measured using a stopwatch, with two timers located right beside the finish line. The timers were instructed to start the stopwatch at the start command and stop it as the runner had one foot over the finish line. The average time from the two recorded values in seconds was used for all data analysis as 400m time.

Day two testing included an isometric mid-thigh pull test (IMTP) and a 2km time trial. Before the IMTP participants completed a 5-minute warm-up on the bike, followed by a standardized warm-up which included 3 sets of 5 clean- grip mid-thigh pulls. The protocol for the IMTP was based on that described in previous literature (Thomas et al., 2015). Participants could select their preferred knee and hip angles, and the immovable bar used for the test was positioned at mid-thigh position. The bar height was adjustable to allow testing of different sized athletes. The rack holding the bar was anchored to the floor. After setting the appropriate bar height, the participants stood on the force plate and their hands were strapped to the bar with lifting straps. Before testing maximal effort, each athlete started with two warm-up pulls, one at 50% and one at 75% of maximum effort, with one-minute rest between. For the maximal pull, participants were given the countdown “3,2,1, Pull!”. Each athlete performed 2 to 4 maximal IMTP tests that lasted 4 seconds, separated by 2-minute recovery periods. During each trial they were instructed to pull as fast and as hard as possible while pushing their feet down into the force plate. Participants were given verbal encouragement during each trial. The best two trials for each athlete were used for subsequent data analysis as measured by PF values. The average maximum force (*N*) from the two trials recorded during the 4 seconds of the test was recorded as PF. Rate of force development was recorded at the time interval 0-150 ms ($N{\cdot}s)^{-}$, based on the typical ground contact time (GCT) during distance races (Hayes & Caplan, 2012).

After the IMPT testing, participants completed their usual pre-practice 15-minute warm-up prior to the 2K time trial, described in more detail above. The warm-up included light aerobic exercise, dynamic stretches and 2 sets of 100m sprints at 75% effort. All the runners completed the 2K time trial at the same occasion, on a 400m flat outdoor running track. Participants were instructed to provide maximal effort over 2000 meters, and were provided verbal encouragement. Times were recorded using a stopwatch, with the timers positioned beside the finish line. Runners wore their own regular trainers that they would use for any practice sessions. Times from the 2K were converted into seconds for data analysis.

Throughout the course of the season, official competition times were tracked and recorded for each participating athlete. After the conclusion of the season, the best 1500m time was selected for each runner, as it was the only event that every single of the participants raced at least once. Times were converted into seconds for data analysis. In addition, all competition performances were converted into scores using the International Amateur Athletic Federation's (IAAF) scoring system (Spiriev, 2022). The highest IAAF score was selected for each athlete, and the scores represented performances in the following races: 800m, 1500m, 3000m, 3000SC, 5000m.

Equipment

Running tests were performed on the Point Loma 400m outdoor track. A stopwatch was used to record times for the 400m and 2K runs. FreeLap timing system was used for the 30m sprint test, connected to an iPad via Bluetooth with the FreeLap app. A Hawkin Dynamics Force Platform was used for the CMJ and IMPT tests, connected to an iPad via Bluetooth connection.

Additionally, a 20 kg bar and a squat rack was used for the IMPT. Race times were retrieved from the website of the Track & Field Results Reporting System (TFRRS).

Statistical Analyses

Statistical analyses were performed using R software in R Studio. Pearson's product moment correlation coefficient analysis was used to assess the relationships between 30m maximal sprint time, 400m maximal sprint time, CMJ height, RFD150, PF, 2K time trial time, 1500m time and highest IAAF score. Correlations were considered weak, moderate and strong at values of $0.3 <= r$, $0.5<= r$ and $0.7 <= r$, respectively (Moore et al., 2013). Multiple linear regression models were constructed to examine the components of 1500m time and highest IAAF score. Variance Inflation Factors (VIFs) were calculated for both models to test for the assumption of collinearity. Relative importance metrics using the Lindeman Merenda and Gold (LMG) method were computed as a supplement to the multiple regression analyses, and to account for the collinearity of the independent variables (Lindeman, 1980; Tonidandel &LeBreton, 2011). Confidence interval tests were based on bootstrapping with 10,000 replications, and were calculated for the relative importance metrics of each variable. Confidence intervals were also used to compare the differences between the relative contributions by each variable. A priori G*Power statistical power analysis was used to determine that 49 subjects would have been needed to achieve an 80% power for the multiple regression analyses; while post-hoc G*Power statistical power analysis was used to determine achieved power with the given sample size (n=10). All statistical analyses were performed at the significance level of 0.05.

Results

The descriptive characteristics of the participants are presented in Table 1. The strength and significance of the relationships among strength, vertical jump, sprint, and distance running variables are presented in Figure 1. Negative moderate correlations (r = -0.67 to -0.57; $p < 0.1$)

were observed between 2K time and highest IAAF score, RFD and 1500m time; and between 400m time and both CMJ and RFD. In addition, 30m time was observed to be moderately correlated with mRSI, RFD, highest IAAF time and 1500m time (r= -0.65 to -0.56; $p < 0.1$); and strongly correlated with CMJ height ($r = -0.77$; $p = 0.01$). A positive moderate correlation was observed between CMJ height and PF ($r = 0.59$; $p = 0.07$). Positive strong correlations (r = 0.72-0.76; $p < 0.05$) were observed between 2K and 1500m time; CMJ height and mRSI; and between RFD and highest IAAF score. Strong correlations were observed between 400m time and 30m time ($r = 0.85$; $p < 0.005$), highest IAAF score ($r = -0.80$; $p < 0.0005$), as well as 1500m time (r = 0.90; $p < 0.0005$). Highest IAAF score and 1500m time were observed to be strongly correlated ($r = -0.97$; $p < 0.001$).

Results from the multiple regression analysis including all measured variables were insignificant, both for 1500m time 1500m time ($R^2 = 0.8496$; F [7,2] = 8.26, $p = 0.1122$) and highest IAAF score ($R^2 = 0.8151$; F [7,2] = 6.668, $p = 0.1366$). Post-hoc G*Power statistical power analysis showed that the achieved power was 7%, based on 2K time ($f^2 = 0.03$). Beta coefficients, significance values and raw relative importance metrics with 95% confidence intervals are presented in Table 2, and collinearity statistics are reported in Table 3. Briefly, the results of the relative importance analyses indicate that a weighted linear combination of our seven variables explained roughly 97% of the variance in the 1500m time criterion (R^2=0.9666) and about 96% in the highest IAAF score criterion ($R^2 = 0.9589$).

Based on the relative importance analysis, out of the seven variables 400m time, 2K time, 30m sprint time and RFD were the most important variables. In case of the 1500m time, 400m time contributed to 34.90% of total R^2, while the relative importance of 2km time was 20.91%. The relative importance of the 30m sprint time (14.94%) and RFD (14.76%) were almost identical. For highest IAAF score, 400m time explained 37.48% of R^2. For highest IAAF score the second most important variable was RFD, with a rescaled relative importance of 20.36%. The relative importance of the 2K (17.26%) slightly exceeded the importance of 30m sprint time (13.84%). For both models, variables related to jumping ability (CMJ height and mRSI) were not as important, and PF had the smallest amount of contribution to the overall R^2. Figure 2 and Figure 3 illustrate the rescaled relative variable importance for 1500m time and highest IAAF score, respectively.

Bootstrap confidence intervals comparing the differences between paired relative contributions revealed that the difference between the relative importance of 30m time, 2K time and RFD was not statistically significant both for 1500m time and highest IAAF score. All other paired combinations showed statistically significant differences in the relative importance of variables, except for CMJ height – mRSI, and mRSI - PF. Based on this we can conclude that the single most important variable in each case was 400m time, followed by a similar relative contribution from 30m time, 2K and RFD; while CMJ height, mRSI and PF were relatively less important.

Discussion

The purpose of the present study was to investigate the relationship between certain strength and muscle power factors and distance running performance. The main findings of the study were the following: (1) moderate to strong correlations were observed between the season best 1500m time and 400m time, 2K time, RFD150 and 30m time and between highest IAAF score and 400m time, 2K time, RFD150 and 30m time; (2) the relative importance of 400m time was the highest for both 1500m time and highest IAAF score, followed by statistically equal contributions by 2K time, RFD150 and 30m time.

The correlations observed between 2K time and distance running performance as measured by season best 1500m time and IAAF score was not surprising based on the current understanding of energy system contributions to different running events. In general, the contribution of the aerobic system increases as the duration of the run increases (Duffield & Dawson, 2003). A study by Duffield and Dawson (2003) reported that during a 1500m run the aerobic system contributes to about 85.5% of the energy, while the anaerobic contribution is about 14.5%. The relative energy contribution of the aerobic system is similar for a 2K and 1500m run (Duffield & Dawson, 2003), therefore seeing the strong correlation between 2K time and 1500m time in the current sample was expected. The IAAF score was based on the best performance of each athlete in events ranging from 800m -5000m, thus observing a slightly weaker relationship (r = -0.67, p<0.05) is in line with expectations.

Sprinting ability was observed to be strongly correlated with long-distance running performance in a study by Yamanaka and colleagues (2019). They reported significant correlations between 5000m season best time and 100m sprint time (r = 0.68, p = 0.014), and 400m sprint time (r = 0.85, p < 0.001); and between 10K season best time and 100m sprint time (r = 0.72, p = .009 and 400m sprint time (r = 0.85, p < 0.001) (Yamanaka et al., 2019). The results of the current study support these findings, as similar correlations were observed between season best race times and 30m sprint (r = 0.61-0.65, p < 0.05) as well as 400m sprint (r = 0.88-0.90, p < 0.001).

Jumping ability, as a measure of muscle power, is significantly correlated with performance in shorter sprinting races such as 60m (r = 0.97, p < 0.05) or 200m sprint (r = 0.97, p < 0.05) (Hudgins et al., 2013). In the current study, the correlations between vertical jump variables such as CMJ height and mRSI, and sprinting ability (30m time, 400m time) were present, but less strong and significant compared to the findings of Hudgins et al. (2013). However, it is important to note and in the study by Hudgins et al. (2013) the athletes were sprinters while the present study’s sample only included distance runners, which could explain the difference in results. In the same study, Hudgins et al. (2013) also reported strong significant correlations (r =0.71 to 0.83, $p < 0.05$) between longer running events (800m – 5000m) and jump distance.

In the present study, there were no significant relationships observed between CMJ height or mRSI and 1500m time or IAAF score. In the current study, only the variables that were biomechanically similar to running presented strong correlations with measures of distance running performance. Only weak relationships were observed between jumping ability, reactive strength ability or maximal strength and distance running performance. This might be due to the fact that the runners completing the study did not have strength or plyometric training as part of their training regimen, and as a result have underdeveloped SSC ability, explaining the lack of correlation with running performance. In the current study, relationships between basic physical characteristics were present, such as the relationship between jumping and sprinting ability, as outlined above. These findings could indicate that the runners included in the current study might not be leveraging certain neuromuscular capacities in their running, such as reactive strength ability, lower leg power or SSC ability. Hence improvements in this area might result in improved distance running performance, as previous studies have shown (Beattie et al., 2014; Nummela et al., 2006; Spurrs et al., 2003).

Another potential explanation for the lack of correlations between jumping and distance running ability is that these relationships might remain low even with training, because other fitness qualities are so much more important. The relative importance analysis suggests that even with training, correlations between distance running and jumping ability won’t be as high as those observed between mode-specific measures and distance running performance. In either case, in the current sample of distance runners CMJ may not be a good measure or predictive tool of running performance. Mode-specific measures of the SSC, such as a short sprint, might be more accurate tools to utilize. However, CMJ could still be useful as a monitoring tool, assessing the readiness of the neuromuscular system, as outlined in previous literature (Balsalobre-Fernandez et al., 2016).

Isometric mid-thigh pull characteristics might be a good indicator of running performance, according to the results of a study by Lum et al. (2020). All variables extracted from the IMTP, including peak force and rate of force development (0-150 ms) had significant correlations with lower leg stiffness (r = 0.41 to 0.49, $p < 0.05$); and all RFD150 measures were significantly correlated to RE (r = -0.44 to -0.68, $p < 0.05$). In the present study, PF did not have any significant correlations with any of the variables related to running performance. However, RFD150 had moderate to strong correlations with all running measures (30m time, 400m time, 1500m time, highest IAAF score). During a race, runners who are able to maintain a good stride length without overextending and at a good frequency will tend to run faster (Anderson, 1996). Overextending can lead to braking forces, and slowing down, as well as reduced RE and increased chance for injury (Schubert et al., 2014). In turn, runners who are able to develop force more quickly will have better RE and run faster (Beattie et al., 2017). Moreover, the time interval for RFD150 (0-150ms) measured in the present study is similar to the average GCT of elite women distance runners competing in the 1500m (180 ± 14 ms) and 800m (171 ± 15 ms) (Hayes & Caplan, 2012). These results suggest that runners who were able to increase force within the same GCT window can theoretically lengthen their stride without overextending, which will result in faster running times if the same frequency is maintained.

The multiple regression model was not significant for either the 1500m time or the IAAF score, with none of the individual variables being significant, except for the intercept in the model for IAAF score. Since previous literature outlines that aerobic ability, as well as anaerobic power are both important in predicting distance running performance (McLaughlin et al., 2010;

Nummela et al., 2006), the lack of significance shown in the present sample could be attributed to the small sample size.

The results of the relative important analysis reflect the trends observed from the correlational analysis. Overall, in the present study the mode-specific measures of ability tended to correlate with running performance more strongly, and were of greater importance based on the relative importance analysis. The importance of mode-specific modalities for measuring athletic ability in not a novel concept. For example, it has been reported that trained runners are able to reach higher VO_2max values when tested on the treadmill as opposed to the cycle ergometer (McConnell, 1988), whereas competitive cyclists do better when tested on the cycle ergometer instead of the treadmill (McArdle & Magel, 1970).

The most important variable in the model was 400m time, both for 1500m time (LMG = 0.34) and highest IAAF score (LMG = 0.36), and the difference in its relative importance was statistically significant from the relative importance of all other variables. Because the 2K time trial relies more heavily on the aerobic energy system than the 400m sprint, we hypothesized that the 2K time would be the most important variable in both of the models, instead of the 400m time. Based on the authors experience as former endurance athletes, this result might be explained by the differences in a 400m time trial versus a 2K time trial, and the ways they could relate to running conditions in a race. During a time-trial, athletes did not have the same psychological arousal as they would in a race where they are motivated to beat runners from other teams. Given this, at the end of a 2K time trial athletes may encounter different metabolic stressors than at the end of a middle or long distance race (ex. lactate build-up during a strong finish). On the other hand, a 400m sprint might be short and fast enough even under the conditions of a time trial, making it a better representation of the physiological demands encountered at the finish of a race.

However, it is possible that the relative importance of a maximal 400m sprint time is actually a better predictor of race performance when it comes to a homogenous sample of distance runners. In a sample of non-trained individuals, 2K time might be a better predictor as there would be greater variance in their aerobic ability. In the case of trained runners, however, it is safe to assume that all participants have above average aerobic abilities. For this reason, the difference in the performance of trained runners might be better explained by how quickly they can complete a 400m sprint, which relies on speed endurance, efficiency of the glycolytic system and ability to tolerate lactate accumulation (Nummela et al., 1992). Moreover, as mentioned previously, 400m sprint time was observed to be strongly correlated to long-distance performance (r=0.69 to 0.85, p <0.05) (Yamanaka et al., 2019). Sprinting ability can be important in middle- and long-distance events as well, since the ability to kick and finish strong in a race can be what separates the most successful athletes from the rest (Yamanka et al., 2019). Previous studies indicate that there is a lot of variation in running velocity during world-class running performances and the final kilometer of 5000m and 10000m races tend to be significantly faster than the middle section of the race (Tucker et al., 2006). As an example, the winner of the women's 5000m race in the 2020 Tokyo Olympics completed the closing lap of the race 57.36 seconds, while the starting lap of the race was only 75.0 seconds, and the average pace per lap for the winner was 70.08 seconds. In the same race, the time that separated the podium finishers from the rest of the field was only 0.75 seconds. This suggests that sprinting ability might be an essential indicator of performance for elite distance runners, especially when it comes to the final laps of a race. In the current study, difference between the relative importance of 2K and 30m time was not statistically significant. This means that sprinting ability was as important as 2K time when looking at both 1500m time and highest IAAF score. These findings support the ideas of Noakes et al. (1987), who suggested that endurance performance might not only be limited by factors related to oxygen uptake, but also by certain muscle power factors that are related to maximal power production. Noakes suggested that peak treadmill running velocity can be a similar predictor of distance running performance as lactate threshold (Noakes, 1990).

Besides the running specific variables, results of the current study indicate that RFD150 (0-150 ms) was also relatively important for both 1500m time and highest IAAF score, while PF was observed to be the least important variable. Peak force is a measure of maximal strength and refers to the maximum amount of force produced during a given window of time; while rate of force development is a measure of explosive strength and refers to how fast an athlete can develop force. Peak force has been associated with the sport of weight lifting (Haff et al., 2005), vertical jump performance (Khamoui et al., 2011; Kraska et al., 2009), as well as other measures of athletic ability (Spiteri et al., 2014; Stone et al., 2004). Previous studies suggested that an increase in maximal strength could help improve distance running performance through improving RE (Storen et al., 2018), while others observed significant correlations between peak force and running performance (Lum et al., 2020). However, there are few articles that look at strength characteristics of distance runners, and some studies found that maximal strength training might not be helpful for distance runners (Vikmoen et al., 2016). In the present study, the only correlation in regards to PF was observed between CMJ height and PF (r = 0.59, p < 0.1).

It has been proposed that for distance runners, explosive and reactive strength characteristics might be of superior importance over maximal strength characteristics (Beattie et al., 2017). However, there is a positive correlation (r = 0.63) between maximal strength, explosive and reactive strength qualities in athletes (Dymond et al., 2011). In the current study, the correlation between PF and RFD150 was weak (r = 0.44, p = 0.20), and PF was not relatively important in either of the models. Rate of force development was significantly correlated to running performance in a study by Lum et al (2020), and in the present study as well. These results suggest that when it comes to distance runners, the ability to express force rapidly (RFD150) is more important than the ability to express force over a long period of time (PF).

In the current study, reactive strength or SSC ability, measured by mRSI was also not important relative to the other measured variables and had almost no relationship with distance running performance (r = 0.00 to 0.04). As discussed above, this might be due to the lack of plyometric training in the sample of runners included in the study. Plyometric training can help improve MTS (Spurrs et al., 2003). Athletes with higher MTS can absorb and store elastic energy more efficiently (Spurrs et al., 2003), leading to higher pre-tension before the spring-like action of the foot strike, ultimately resulting in higher GRF (a measure of the vertical forces generated during the contact phase of running) (Kyrolainen et al., 1991). While both mRSI and MTS are similar in that both are dependent on the SSC; effective pre-tension in the lower leg musculature during flight phase developed by distance running training may not correlate with elastic efficiency during countermovement jumps as measured by mRSI.

When taking all variables into account, 96.66% of the variance in 1500m time and 95.89% of the variance in highest IAAF score was explained. However, these results should be interpreted with caution as the multiple regression model used for the relative importance analysis - including all individual beta coefficients - was not statistically significant; and multicollinearity was detected for some of the variables. The primary limitation of this study was in its small sample size. Further, measuring VO_2max in a laboratory setting would have provided a more accurate profile for the aerobic capacities of the runners compared to the 2K time trial, during which the conditions were suboptimal. Lastly, we used season best 1500m times and the highest IAAF score from performances throughout the season as a measure of distance running ability. However, some of the athletes stopped competing earlier in the season than others due to injury or sickness. As a results, their best 1500m time or IAAF score might not be an accurate representation of their potential, as track athletes tend to peak and perform the best towards the end of the season with proper training. Another limitation is that athletes completed the 2K time trial in suboptimal conditions (strong winds during the time trial). On account of this, athletes might not have been able to give a true maximal effort, which might have affected some of the results seen in this investigation.

Conclusions

The findings of the current study suggest that sprinting ability (30m sprint and 400m sprint) and explosive strength characteristics (RFD150) might be important indicators of distance running performance in addition to aerobic capacity. Research in this area is still in its infancy, but past studies observed relationships similar to those reported in this investigation. In the present study, 400m time, RFD, 30m time and 2K time all had moderate to strong relationships with distance running ability, measured by season best 1500m time and highest IAAF score from all around race performances during the season; and were the most important variables in the relative importance analysis. Therefore, the results of this study reject one out of the four null hypotheses (3), but fail to reject the other three (1,2,4). Based on these findings, enhancing sprinting ability and explosive strength characteristics might be more important for distance runners than previously thought. Moreover, 400m time can be a potential predictor of distance running ability. Future investigations are needed to evaluate the relationships explored in the current study in a sample of runners who already do some form of strength or plyometric training. Further research examining the sprinting ability and force developing capacity of distance runners in a larger sample with more statistical power is also recommended.

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Table 1

Descriptive characteristics of participants (n=10)

Variable	Mean ±SD	Min-Max
Age (years)	20.8 ± 1.69	19 - 24
Height (cm)	166.2 ± 7.67	152 - 178
Weight (kg)	61.34 ± 6.12	47.62 - 69.43

Table 2

Summary of relative weight analysis using the LMG method

Predictor	*b*	*p*	*β*	*LMG*	*CI-L*	*CI-U*
Criterion = 1500m time (R^2 = 0.8496; *F* [7,2] = 8.26, *p* = 0.1122)						
Intercept	7.729e+01	0.560				
2K time	1.757e-01	0.533	0.2164	0.2021	0.1502	0.2607
400m time	2.885e+00	0.265	0.6659	0.3374	0.2895	0.3942
30m time	-1.072e+01	0.708	-0.1621	0.1444	0.1226	0.1793
CMJ height	-1.812e+02	0.495	-0.3468	0.0600	0.0474	0.0886
mRSI	8.924e+01	0.396	0.3374	0.0547	0.0308	0.0946
PF	1.281e-02	0.545	0.1829	0.0253	0.0233	0.0402
RFD150	-4.542e-03	0.292	-0.3474	0.1426	0.0958	0.2029
Criterion = IAAF score (R^2 = 0.8151; *F* [7,2] = 6.668, *p* = 0.1366)						
Intercept	2181.30	0.097				
2K time	0.1439	0.934	0.0299	0.1655	0.1224	0.2288
400m time	-30.39	0.133	-1.1849	0.3594	0.3022	0.4268
30m time	177.43	0.390	0.4534	0.1327	0.1160	0.1638
CMJ height	-541.03	0.743	-0.1750	0.0460	0.0403	0.0644
mRSI	99.77	0.872	0.0637	0.0339	0.0241	0.0652
PF	-0.06	0.677	-0.1354	0.0262	0.0226	0.0474
RFD150	0.03	0.274	0.4055	0.1952	0.1338	0.2750

Note. *b* = unstandardized regression weight, *β* = standardized regression weight, *LMG* = raw relative importance metrics (within rounding error raw weights will sum to R^2), *CI-L* lower bound of confidence interval of raw relative weight (*LMG*), *CI-U* upper bound of confidence interval of raw relative weight (*LMG*).

*** = $p < 0.001$, **= $p < 0.01$, *= $p < 0.05$.

Table 3

Collinearity Statistics

Variable	Tolerance	VIF
2K time	0.199	5.035
400m time	0.889	11.261
30m time	0.119	8.432
CMJ height	0.095	10.506
mRSI	0.167	5.928
PF	0.261	3.831
RFD150	0.278	3.591

Note. VIF values over 10, and Tolerance values less than 0.1 indicate multicollinearity.

Figure 1

Correlation matrix of all variables with significance

	400m time	**30m time**	**CMJ height**	**mRSI**	**PF**	**RFD150**	**IAAF score**	**1500m time**
2K time	0.48 0.16	0.29 0.42	0.19 0.61	0.20 0.58	0.35 0.32	-0.46 0.18	-0.67 0.03*	0.72 0.02*
400m time		0.85 0.002*	-0.60 0.07	-0.22 0.53	-0.37 0.29	-0.57 0.08	-0.88 0.0009*	0.90 0.0004*
30m time			-0.77 0.01*	-0.58 0.08	-0.46 0.18	-0.56 0.09	-0.61 0.06	0.65 0.04*
CMJ height				0.76 0.01*	0.59 0.07	0.26 0.28	0.27 0.46	-0.31 0.39
mRSI					0.37 0.29	0.27 0.45	0.00 0.10	0.04 0.92
PF						0.44 0.20	0.21 0.56	-0.15 0.68
RFD150							0.73 0.02*	-0.65 0.04*
IAAF score								-0.97 0.00*

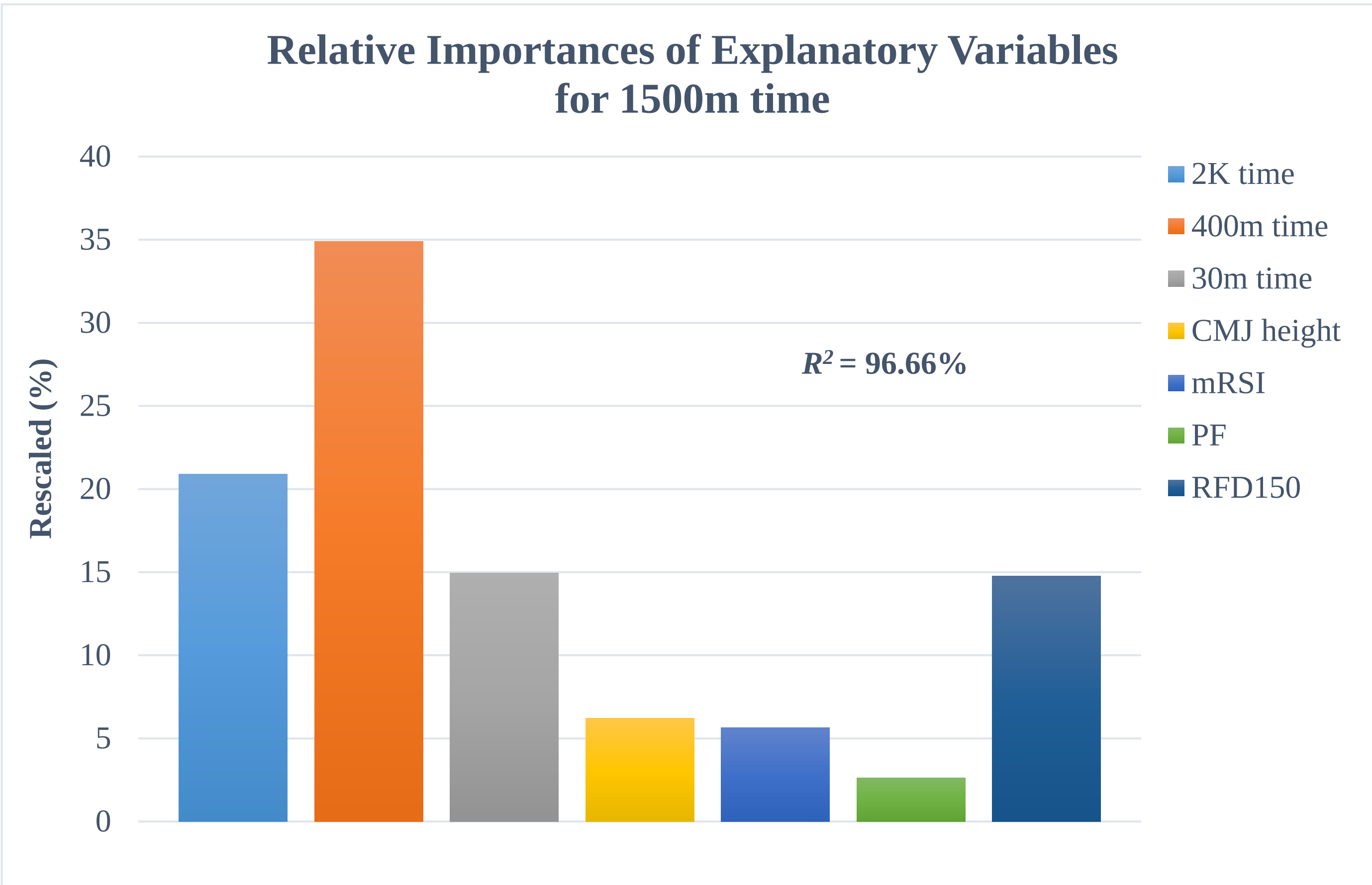
1	positive
0	neutral
-1	negative

Note. IAAF score = highest IAAF score

*$p < 0.05$

Figure 2

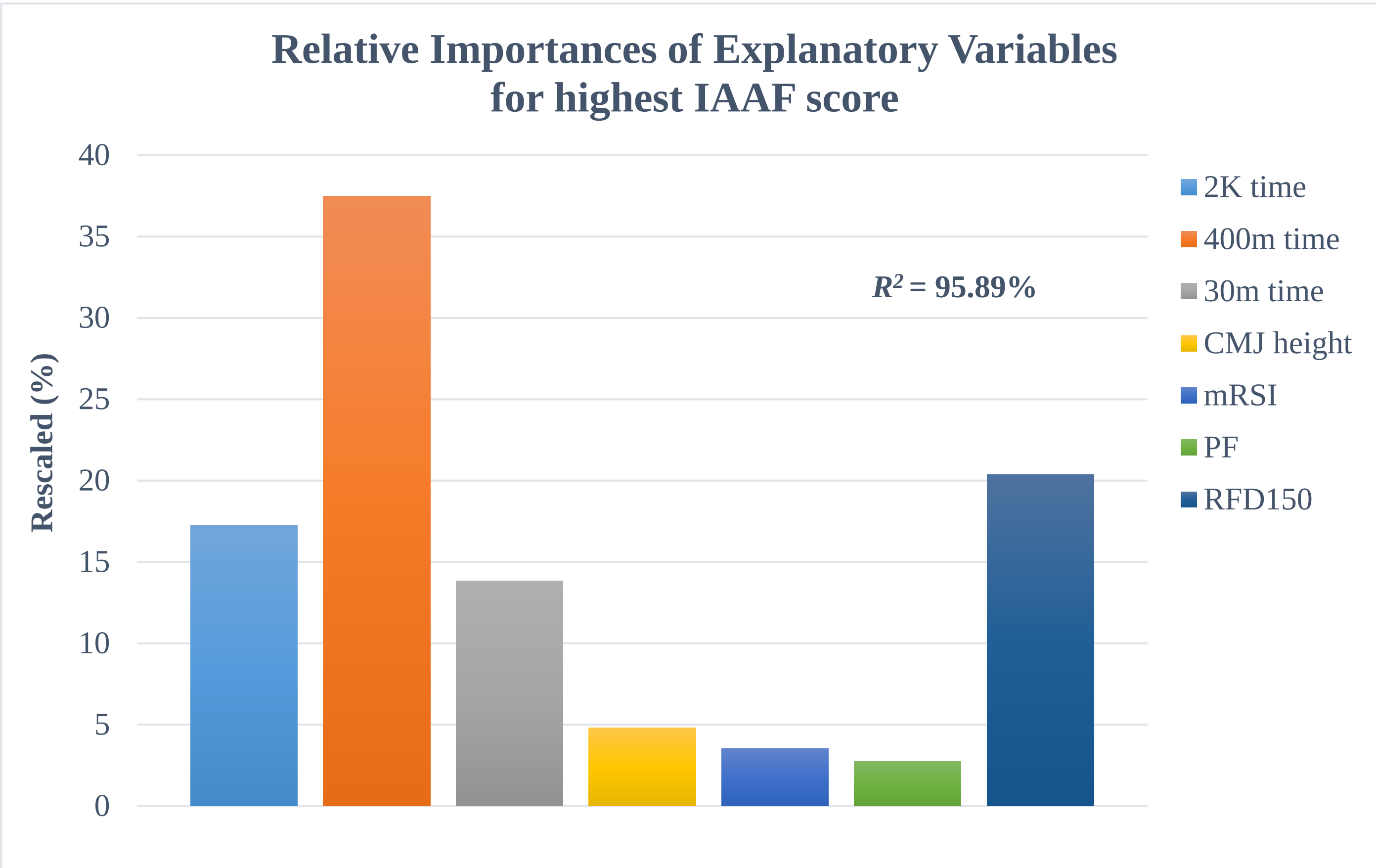
Rescaled variable importance estimates for 1500m time using the Lindemann, Merenda and Gold (LMG) method



Note. Rescaled relative importance metrics sum to 100%.

Figure 3

Rescaled variable importance estimates for highest IAAF score using the Lindemann, Merenda and Gold (LMG) method



Note. Rescaled relative importance metrics sum to 100%.