Physiological components of fitness as determinants of sprinting performance: muscular strength, anaerobic power, and aerobic capacity

SCOTT LEE

WRITER’S COMMENT: While lectures and exams are essential components of my undergraduate education at UC Davis, I often feel confined to a passive role of accepting the information handed to me. Thus, I relish any opportunity to pursue my own academic interests. When Pamela Demory assigned a review article for her English 104E (Science Writing) class, I took full advantage of the academic freedom she granted me. I decided to combine my experiences as a sprinter on the UC Davis Track and Field team and an intern with the UC Davis Sports Medicine Group and investigate the physiological determinants of sprinting performance. My interest in the subject, along with expert editing by Professor Demory, made it much easier to synthesize the dense scientific information presented in the journal articles. The insight I gained into various testing protocols and training programs helped me understand the principles behind my own athletic training. I also hope that the article will help educate others about the growing field of applied biomedical research, the lack of research dedicated to sprint-based events, and the potential health and fitness benefits of additional research. Furthermore, my response to this assignment has helped develop advanced fitness testing on members of UC Davis athletic teams.

—Scott Lee

INSTRUCTOR’S COMMENT: Scott wrote this fine article in response to a standard assignment in English 104E (Science Writing): the scien-
tific review article. This challenging assignment requires students to find a cutting-edge area of research in their field, research that topic in the scientific literature, and then synthesize that material for an audience of interested professionals. Scott succeeds admirably on all counts. He found a topic that allowed him to combine his experience as a track and field athlete with his academic work as a pre-med student and researcher: current research on the physiological components of fitness—specifically as they relate to sprint performance. One of the most commendable aspects of this paper is its focus: Scott chose to research the literature on sprint performance only, explaining that research has traditionally focused on long-distance running, but then subdivides that small topic into the three inter-related factors of muscular strength, anaerobic power, and aerobic capacity. The result is a wonderfully in-depth analysis of recent research on the topic.

—Pamela Demory, University Writing Program

Abstract

In contrast to the numerous studies on long-distance running, researchers have been unable to reach a consensus regarding the measurement, relative contribution, and predictive accuracy of physiological variables on sprint performance. Developments in this area of Sports Medicine have the potential to improve training programs and produce gains in sprint performance similar to those produced by research on endurance running events. Recently, researchers have investigated the role of muscular strength, anaerobic power, and aerobic capacity in sprinting events. Concentric and eccentric muscle strength have been correlated with sprinting performance because they closely resemble sprinting in both the duration and application of force. Anaerobic power has also been indicated as an important component of sprinting, one that has been traditionally measured through blood lactate tests. While such tests are strongly correlated to sprint performance, new anaerobic measurements like Peak Oxygen Deficit (POD), which compares the difference between expected and actual energy expenditure, may provide even greater
predictive accuracy. In fact, aerobic metabolism may play a larger role in sprint-based events than previously thought. Thus, endurance variables such as VO\textsubscript{2max} may also help determine sprint performance. Given the prevalence of sprinting in a variety of sports, sprint-based research has the potential to affect a large percentage of the athletic community by helping to develop training programs, record training progression, and predict sprint performance.

**Introduction**

Athletes undergo a process of self-selection in determining which track events to specialize in (2). This is undoubtedly due to both genetic and environmental components that help shape an athlete’s abilities and limit his/her physical potential. The majority of research on track and field athletes has concentrated on long-distance runners, thereby developing physiological measures such as VO\textsubscript{2max} and blood lactate tests that are accurate indicators of long-distance running performance. Yet given the greater number of sprint-based events in track and field as well as the high frequency of sprinting in popular team sports such as football and basketball, most research does not accurately reflect the nature of American sports. The lack of sprint-based research has hindered the development of methods for measuring physiologic variables related to high-intensity sprints (14). Research in this field has the potential to improve the design of sprint training programs and help track an athlete’s progress. Such developments may lead to large gains in performance similar to those experienced by endurance athletes that use VO\textsubscript{2max} values to create endurance-training programs (5). However, while researchers agree that a successful sprinter combines a large anaerobic work capacity, explosive strength, and aerobic fitness with biomechanical efficiency and skill, there is considerable controversy
over the measurement, relative contribution, and predictive value of these traits for sprint performance (10). Thus, the purpose of this review is to investigate these controversies and uncover the predictive power of three related physiological components of fitness—muscular strength, anaerobic power, and aerobic capacity—in determining sprint performance up to 400-meters.

**Functions of Muscular Strength: Acceleration and Top-end Speed**

Researchers commonly agree that sprinting requires a high level of muscular strength, particularly in the legs and trunk, to optimize propulsive forces off the ground while limiting braking forces on the body (12). In a study conducted with female sprinters from the University of New Mexico Track team, Meckel *et al.* (9) found heavier one-repetition max (1RM) squat to be strongly correlated with faster 100m performance. This finding indicates that leg strength is a necessary component of successful sprinting. However, other studies have further separated strength measurements into concentric and eccentric contractions in an effort to mimic the specific muscle contractions that occur during sprint events and increase the predictive accuracy of muscular strength measurements for sprint performance (12, 15).

**Transient Phases of Concentric and Eccentric Contractions**

The acceleration phase covers approximately the first 30–50m of a race and is primarily composed of concentric contractions of the hip and knee extensors (15). Young *et al.* (15) examined Australian Junior National sprinters and found that performance in a 2.5m block start was strongly correlated to the maximal force developed from a 120° knee-bend vertical jump.
This strong correlation is a result of the specificity of the vertical jump to the acceleration phase. Not only is the 120° knee-bend vertical jump primarily a concentric movement, the 120° angle mimics the optimal knee-angle for initial force production out of the blocks (15). Sleivert and Taingahue (12) report a similar correlation between sprint acceleration and concentric strength. However, unlike the 120° knee-bend vertical jump used by Young et al. (15), this study employed a 1RM split squat that produced hip and knee angles seen during the initial strides out of the blocks (15). Taken together, both the 120° knee-bend vertical jump and 1RM split squat provide researchers with strength measures to determine performance out of the blocks and through the entire acceleration phase of sprint events (12, 15).

While concentric contractions can produce quick acceleration, eccentric contractions maximize top-end speed by slowing the forward swing of the legs and placing foot-strike below the hip joint (12). Top-end speed is most often obtained after 50–70m in the 100m and after 110–150m in the 200m. Young et al. (15) observed a strong correlation between top-end speed and the force generated over 100ms during counter-movement jumps (CMJ). CMJ is specific to the top-end phase of sprinting as it is not only an eccentric contraction, but also produces a ground-contact time that closely corresponds to the 101ms contact time observed in sprinters running at top speed (15). These results indicate that top-end speed is more dependant on the impulse of force production than the magnitude of force produced (12).

Implications on the Strength Training Paradigm
Most sprint-training programs dedicate a considerable amount of time to the development of muscular strength (9). However, determination of strength by 1RM may not be the best predic-
tor of sprint performance. While Meckel et al. (9) did find 1RM to be correlated with 100m sprint performance, this strength measurement does not distinguish between concentric and eccentric strength, and as a result, is less able to predict an athlete’s performances in specific phases of a race (15). While 1RM squat is a concentric contraction and can help build muscular strength for acceleration, it does not position the knee and hip at the 110–120° angles experienced during the acceleration phase. Furthermore, 1RM squat trains the athlete to produce force over a period of time greater than 100ms and does not elicit the specific eccentric contractions that occur when running at top speed. A heavier 1RM squat may simply reflect better overall leg strength and may account for the performance differences observed between elite and average sprinters (15). However, that is not to say that elite-level sprinters are better in both acceleration and top-end phases. For example, a sprinter may possess a high 1RM squat and an excellent acceleration phase, but he or she may experience subpar performances in later race phases as a result of weak eccentric strength and corresponding lower top-end speed. By using more sprinting-specific strength measurements, athletes may experience improved performance by identifying weaknesses in both types of muscular strength and training for specific aspects of sprint races.

The Role of Anaerobic Power in Sprint Performance

Peak Blood Lactate as a Predictive Measure

Blood lactate tests have often been used to determine long-distance running performance. However, researchers report little or no correlation between peak blood lactate ([Lac]b) values and running velocity in distance events. [Lac]b has only been strongly correlated to average race velocity in events up
to 800m, suggesting that the measurement is more relevant to sprint events (6). The formation of lactate in the blood signals the activation of the glycolytic energetic pathway. This pathway mobilizes energetic substrates faster than aerobic pathways and helps power the rapid muscle contractions necessary for sprinting (7). In one study, elite 400m runners produced higher [Lac]b values immediately after an international competitive race than runners whose [Lac]b values were measured after maximal exercise on treadmills. Consequently, researchers believe that post-competition tests provide more accurate information regarding the contribution of anaerobic metabolism to total energy expenditure (6). A French study further distinguished the lactate profile of sprinters by comparing their lactate production curves to those of 800m runners (2). Both groups completed 420m at the same pace, but researchers found that sprinters produced higher [Lac]b and larger ∆lactate ([Lac]b – [Lac]rest) values than 800m runners (2). The higher lactate values produced by sprinters may be as much a result of their increased percentage of Type II fibers and their ability to produce lactate as it is their reduced capacity to clear lactate via oxidative metabolism (2). This is consistent with other studies that found sprinters to have higher glycolytic enzyme activity than endurance athletes (as cited in [7]). However, researchers indicate that the accumulation of lactate and its associated H+ ion reduce the ability of skeletal muscle to produce force (1). Thus, lactate tests can be used to determine an individual’s metabolic profile and consequently predict his or her success at sprint-distances. A successful sprinter possesses a high-percentage of Type II fibers and can produce large amounts of lactate through anaerobic and glycolytic metabolism. Furthermore, the shorter duration of the sprint events limits the fatigue and decreased force production associated with slow lactate clearance and lactate/ H+ ion ac-
A Finnish study attempted to distinguish the metabolic profiles of sprinters specializing in either the 100m or 400m. Both sprint groups produced identical [Lac]₀ after completing maximal 20-second sprints (10). While this may indicate that [Lac]₀ is not able to predict an individual’s performance within the sprint events, it is important to note that the individuals who comprised the 400m group were of much higher athletic caliber than individuals in the 100m group, and this most likely had a significant effect on the data. The level of glycolytic enzyme activity may be a better predictor of performance within the sprint events; individuals better suited for the 100m may possess faster isoforms of glycolytic enzymes and be able to reach [Lac]₀ and obtain energy from glycolytic sources in a shorter amount of time (7).

While researchers are still unsure of the predictive accuracy of [Lac]₀ for performance within sprint events, most agree that sprint training induces enzymatic and ionic changes toward more efficient energetic mobilization (4, 7). After completing a period of bicycle sprint training, subjects completed sprint tests at their pre-training maximal intensity and showed an improved ability to maintain muscular contractions while also producing a lower [Lac]₀ (4). Such studies demonstrate how [Lac]₀ can be used to track the efficacy of a sprint-training program. When blood lactate concentration is plotted against workload, the effects of training are indicated by a decrease in blood lactate at the pre-training maximal workload, a higher maximal workload, and a higher [Lac]₀ (4).

Recent research has investigated the accuracy of Peak Oxygen Deficit (POD) measurements in assessing anaerobic power. POD is defined as the difference between the estimated oxygen demand of a given activity and the actual volume of oxygen consumed (14). POD has the potential to be a
more accurate predictor of sprint performance than $[\text{Lac}]_b$ as it provides a more direct measurement of anaerobic metabolism (14). Unlike $[\text{Lac}]_b$, which not only fails to account for energy derived from the alactic phosphagen system, but also measures a product of anaerobic metabolism that is subject to removal from the blood, POD estimates energy extracted from both the lactic and alactic systems (8). A study conducted by the University of Georgia found that POD measured during treadmill runs to exhaustion was a stronger predictor of performance at 100 to 400m than $[\text{Lac}]_b$; POD accounted for 50% of the variance in running time at these distances, whereas $[\text{Lac}]_b$ only accounted for 26% of the performance variance (14).

However, a similar study found that POD did not differ significantly between highly competitive sprinters and recreational runners with no anaerobic training, even though these two groups possessed marked differences in sprinting ability (11). The conflicting results on POD may be attributed to the variability in estimating oxygen demand for a given activity. This value is estimated by performing linear extrapolation of oxygen uptake vs. treadmill speed graphs obtained during sub-maximal exercise. This estimation may introduce some error and decrease the predictive value of POD (14). Nevertheless, Weyand et al. (14) and Olesen et al. (11) provide promising results regarding POD that will have interesting implications for future research and the development of sprint-training regimens.

**Aerobic Capacity: Are Endurance Variables Detrimental to Sprint Performance?**

*Aerobic Metabolism’s Energetic Contribution in Sprinting*

Aerobic fitness, commonly denoted as $\text{VO}_{2\max}$, is not normally
associated with maximal-effort sprints. However, research has shown that in subjects with similar \([\text{Lac}]_b\) values following treadmill runs to exhaustion, a higher \(\text{VO}_2\text{max}\) proved to be indicative of better sprint performance (11). While this does not conclusively show that \(\text{VO}_2\text{max}\) and aerobic fitness are more accurate predictors of sprinting performance than \([\text{Lac}]_b\) or POD, it does suggest that aerobic metabolism may provide a greater percentage of total energy in anaerobic efforts than originally thought (13). An Australian study involving elite sprinters used POD values obtained from simulated sprint events on a treadmill to determine the energetic contribution of aerobic metabolism. Aerobic energy sources accounted for 29% and 43% of energy over a 200m and 400m race, respectively (13). Furthermore, aerobic metabolism provides more than 20% of total energy immediately at the onset of a 200m sprint while also becoming the primary source of energy after fifteen seconds of running in a 400m sprint (13).

Although the high intensity of sprint events relies heavily on anaerobic energy sources and may never allow an athlete to reach \(\text{VO}_2\text{max}\), when this value is viewed as a measure of aerobic capacity, it may indicate an increased ability to transport lactate from the blood for oxidative metabolism (13, 14). For example, the oxidation of lactate may provide an additional source of energy in the last 30m of the 100m; during this stage, it is impossible to maintain peak power and velocity because the phosphagen system has been depleted and the muscle has a reduced capacity to regenerate ATP. Increases in \(\text{VO}_2\text{max}\) may also reduce the accumulation of H+ ion in active skeletal muscle (4). Thus, an increased ability to transport and oxidize lactate may help maintain force production after depletion of the phosphagen system and provide the athlete with a slight edge to close out the race.

Distance runners often have higher \(\text{VO}_2\text{max}\) values and are
less able to produce high \([\text{Lac}]_b\) values than sprinters, but it remains to be seen whether increased \(\text{VO}_2\text{max}\) values among sprint athletes also cause a reduction in \([\text{Lac}]_b\) values (1). In contrast to the results of Olesen \textit{et al.} (11), Meckel \textit{et al.} (9) found little correlation between \(\text{VO}_2\text{max}\) values and sprint performance. This discrepancy may be attributed to differences in running protocol, since Meckel \textit{et al.} (9) only measured sprint performance over 100m and may not have taxed the aerobic system to the same extent as the exhaustive sprint-protocol employed by Olesen \textit{et al.} (11). However, it seems unlikely that \(\text{VO}_2\text{max}\) and aerobic fitness do not factor into sprint performance in light of the relatively large energetic contribution of aerobic metabolism (13).

\textit{Implications of an Increased Aerobic Component for Sprint Training}

These findings may cause some individuals to question their sprint training. However, most well-rounded training programs provide a considerable endurance base early in the training program as it allows an individual to complete more high quality sprints during training bouts (9). A popular belief is that endurance training impairs an individual’s ability to sprint and detracts from anaerobic sprint-training adaptations. A British study found that a six-week endurance cycling program had absolutely no effect on peak power output or \([\text{Lac}]_b\) when subjects completed a Wingate test (3). While the endurance program was short-term, the study provides encouraging support for an increased role of endurance training in sprint programs. In fact, an individual may not even need to add an endurance component above what he or she already does for sprint training in order to increase aerobic capacity. MacDougall \textit{et al.} (7) found that the intensity of exercise, particularly high intensity-sprint training, may have a greater effect on muscle
oxidative enzyme activity and mitochondrial density than the volume of training. Harmer et al. (4) employed the same sprint training protocol as MacDougall et al. (7) and found that improved sprint performance was a result of increased aerobic capacity rather than improvements in anaerobic power. Such results do not discount the contribution of anaerobic power to sprint performance, but rather provide researchers with an additional variable for testing and training successful sprinters.

**Conclusion**

Although sprint performance is subject to other factors including race-to-race variability, reaction time, lever length, and psychological state, the three physiological components outlined in this review not only have predictive accuracy, but they can also be manipulated through training (3, 4, 7). The trainability of these factors make them ideal candidates to track an athlete’s progression and develop training programs. Furthermore, their predictive accuracy for sprint performance is increased when measured in situations that closely mimic actual race conditions (6, 12, 15). Researchers argue for the use of concentric and eccentric contractions in training and tracking an athlete’s performance in the acceleration and top-end speed phases respectively (12, 15). Anaerobic power is closely related to muscular strength, and both [Lac]_b and POD have been linked to sprint performance (2, 6, 11, 14). POD has purportedly offered greater predictive accuracy than [Lac]_b, but additional studies are needed to confirm this finding (14). In addition, very little research has been able to indicate whether muscular strength or anaerobic power has a greater contribution to sprint performance. Meckel et al. (9) argue that both variables contribute equally to sprint performance, but their results have not been reproduced by other studies. Fur-
thermore, Spencer and Gastin (13) indicate that aerobic metabolism is a larger energetic contributor in sprint events than previously thought, and this development offers an additional variable to train and track an athlete’s progression.

While researchers have found moderate to strong correlations of muscular strength, anaerobic power, and aerobic capacity to sprint performance individually, their predictive accuracy may be further improved if these three components are considered together. Sprinting is an activity that involves the entire body in both concentric and eccentric contractions and the contribution of alactic, lactic, and aerobic energy sources. It remains to be seen whether large gains in muscular strength, anaerobic power, or aerobic capacity have an associated negative effect on other physiological variables. Thus, there is great potential for future research in this field, and the results will have widespread application to a variety of athletic events.

References


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