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REVIEW ARTICLE

The Importance of Muscular Strength in Athletic Performance

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Abstract This review discusses previous literature that has examined the influence of muscular strength on various factors associated with athletic performance and the benefits of achieving greater muscular strength. Greater muscular strength is strongly associated with improved force-time characteristics that contribute to an athlete's overall performance. Much research supports the notion that greater muscular strength can enhance the ability to perform general sport skills such as jumping, sprinting, and change of direction tasks. Further research indicates that stronger athletes produce superior performances during sport specific tasks. Greater muscular strength allows an individual to potentiate earlier and to a greater extent, but also decreases the risk of injury. Sport scientists and practitioners may monitor an individual's strength characteristics using isometric, dynamic, and reactive strength tests and variables. Relative strength may be classified into strength deficit, strength association, or strength reserve phases. The phase an individual falls into may directly affect their level of performance or training emphasis. Based on the extant literature, it appears that there may be no substitute for greater muscular strength when it comes to improving an individual's performance across a wide range of both general and sport specific skills while simultaneously reducing their risk of injury when performing these skills. Therefore, sport scientists and practitioners should implement long-term training strategies that promote the greatest muscular strength within the required context of each sport/event. Future research should examine how force-time characteristics, general and specific sport skills, potentiation ability, and injury rates change as individuals transition from certain standards or the suggested phases of strength to another.

Key Points

This review discusses previous literature that examined the influence of muscular strength on various factors associated with athletic performance and the benefits of achieving greater muscular strength.

Greater muscular strength is associated with enhanced force-time characteristics (e.g. rate of force development and external mechanical power), general sport skill performance (e.g. jumping, sprinting, and change of direction), and specific sport skill performance, but is also associated with enhanced potentiation effects and decreased injury rates.

The extant literature suggests that greater muscular strength underpins many physical and performance attributes and can be vastly influential in improving an individual's overall performance.

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1 Introduction

A number of underlying factors may contribute to an athlete's performance. While sport scientists and practitioners cannot manipulate an athlete's genetic characteristics, an athlete's absolute and relative muscular strength can be enhanced with regular strength training. Muscular strength has been defined as the ability to exert force on an external object or resistance [1, 2]. Given the demands of an individual's sport or event, he or she may have to exert large forces against gravity in order to manipulate their own body mass (e.g., sprinting, gymnastics, diving, etc.), manipulate their own body mass plus an opponent's body mass (e.g., American football, rugby, wrestling, etc.), or manipulate an implement or projectile (e.g., baseball, weightlifting, shotput, etc.). The constant within all of the previous examples that may be considered a limiting factor of performance is the individual's muscular strength. The purpose of this review is to discuss previous literature that has examined the influence of muscular strength on various factors associated with athletic performance and to discuss the benefits of achieving greater muscular strength.

2 Literature Search Methodology

Original and review journal articles were retrieved from electronic searches of PubMed and Medline (EBSCO) databases. Additional searches of Google Scholar and relevant bibliographic hand searches with no limits of language of publication were also completed. The search strategy included the search terms 'maximum strength and jumping', 'maximum strength and sprinting', 'maximum strength and change of direction', 'maximum strength and power', 'strength and rate of force development', 'muscular strength and injury rate', 'strength level and postactivation potentiation', and 'strength level and athletic performance'. The last month of the search was January 2016.

The authors acknowledge that there are other methods of assessing muscular strength (e.g., isokinetic, dynamic strength index, etc.); however, this article focuses primarily on isometric and dynamic measures of strength. Furthermore, the authors acknowledge the disparity between lower and upper extremity strength literature as more scientific literature has examined lower extremity strength. This review uses a descriptive summary of research based on correlational analyses performed in each study. The magnitude of the relationships were defined as 0 to 0.3, or 0 to −0.3, was considered small; 0.31 to 0.49, or −0.31 to −0.49, moderate; 0.5 to 0.69, or −0.5 to −0.69, large; 0.7 to 0.89, or −0.7 to −0.89, very large; and 0.9 to 1.0, or −0.9 to −1.0, near perfect [3].

3 Influence of Strength on Force-Time Characteristics

High rates of force development (RFD) and subsequent high external mechanical power are considered to be two of the most important performance characteristics with regard to sport performance [4–6]. Previous research has indicated that RFD and power differs between starters and non-starters [7–12] and between different levels of athletes [8–11, 13–18]. Due to the importance of RFD and external mechanical power to an athlete's performance, trainable factors that may enhance these variables would be considered of utmost importance.

3.1 Rate of Force Development

Previous research has defined RFD as the rate of rise in force over the change in time, and has also been termed "explosive strength" [19]. The rate at which force can be produced is considered a primary factor to success in a large variety of sporting events [5]. The rationale behind this hypothesis is that a range of sports require the performance of rapid movements (e.g., jumping, sprinting, etc.) where there is a limited time to produce force (∼50 to 250 ms) [20]. Similarly associated with force-time variables, impulse is defined as the product of force and the period of time in which the force is expressed. While impulse may ultimately determine vertical jump and weightlifting performance [21], the importance of RFD cannot be overlooked because a longer period of time (>300 ms) may be needed to reach maximum muscular force [19, 22–25]. Thus, the emphasis of training may be to increase RFD to allow a greater force to be produced over a given time period. This in turn would lead to an increase in the generated impulse or decrease in the time needed to obtain an equal impulse and subsequent acceleration of a person or implement.

Several studies have indicated that gaining strength through resistance training positively influences the RFD characteristics of an individual [19, 26–28]. Another study indicated that maximal muscular strength may account for as much as 80 % of the variance in voluntary RFD (150–250 ms) [20]. In support of these findings, a number of studies have examined the relationships between muscular strength and RFD (Table 1).

Fifty-nine Pearson correlation magnitudes were reported in Table 1 with all of the relationships being positive. Fifty-seven of the reported relationships (97 %) displayed a correlation magnitude of greater than or equal to 0.3, indicating a moderate relationship. Furthermore, 44 (75 %) of the reported correlation magnitudes displayed a large relationship with values of 0.5 or greater. Limited research

Table 1 Summary of studies correlating maximal strength and rate of force development variables

Study	Subjects (n)	Strength measure	RFD measure	Correlation results
Andersen et al. [26]	Healthy, sedentary males ($n = 15$)	MVC of knee extensors	Slope of torque–time curve in incrementing periods of 0–10, 0–20, 0–30,…0–250 ms	$r = 0.69$ (0–250 ms)
Bazyler et al. [29]	Recreationally-trained college-age males ($n = 17$)	1RM BS, 1RM partial squat, IS 90° knee angle, IS 120° knee angle	IRFD 0–250 ms with IS at 90° and 120°	IS at 90° IRFD: $r = 0.55$ (1RM BS), $r = 0.32$ (1RM partial squat), $r = 0.68$ (IS 90°), $r = 0.39$ (IS 120°) IS at 120° IRFD: $r = 0.43$ (1RM BS), $r = 0.42$ (1RM partial squat), $r = 0.45$ (IS 90°), $r = 0.64$ (IS 120°)
Beckham et al. [30]	Male and female intermediate to advanced weightlifters ($n = 12$)	IMTP	IRFD (0–100, 0–150, 0–200, 0–250 ms)	$r = 0.34$ (0–100 ms), $r = 0.42$ (0–150 ms), $r = 0.56$ (0–200 ms), $r = 0.73$ (0–200 ms)
Haff et al. [31]	Elite female weightlifters ($n = 6$)	1RM snatch and clean and jerk	Peak IRFD	$r = 0.79$ (Snatch) $r = 0.69$ (Clean and Jerk)
Kawamori et al. [32]	Collegiate male athletes ($n = 15$)	1RM HPC, Rel 1RM HPC	CMJ and SJ peak RFD	1RM HPC: $r = 0.53$ (CMJ), $r = 0.68$ (SJ) Rel 1RM HPC: $r = 0.56$ (CMJ), $r = 0.64$ (SJ)
Kawamori et al. [33]	Collegiate male weightlifters ($n = 8$)	IMTP	CMJ peak RFD, SJ peak RFD	$r = 0.85$ (CMJ), $r = 0.43$ (SJ)
Kraska et al. [34]	Male and female NCAA division I athletes ($n = 81$)	IMTP	IRFD (not specified)	$r = 0.88$
McGuigan et al. [35]	NCAA division III male wrestlers ($n = 8$)	IMTP	IRFD (not specified)	Not specified
McGuigan and Winchester [36]	NCAA division I male football players ($n = 22$)	1RM BS, IMTP	IRFD (not specified)	Not specified
Stone et al. [37]	International and local-level male cyclists ($n = 30$)	IMTP, Rel IMTP, IMTPa	Peak IRFD	IMTP: $r = 0.46$ Rel IMTP: $r = 0.23$ IMTPa: $r = 0.34$
Stone et al. [37]	National-level male and female cyclists ($n = 20$)	IMTP, Rel IMTP, IMTPa	Peak IRFD	IMTP: $r = 0.68$ Rel IMTP: $r = 0.20$ IMTPa: $r = 0.58$
Thomas et al. [38]	Male collegiate cricket, judo, rugby, and soccer athletes ($n = 22$)	Rel IMTP	Rel IRFD	$r = 0.70$

Table 1 continued

Study	Subjects (*n*)	Strength measure	RFD measure	Correlation results
Zaras et al. [39]	Young male and female track and field throwers ($n = 12$)	1RM BS, 1RM HPC, isometric leg press	Slope of force–time curve during 0–50, 0–100, 0–150, 0–200, and 0–250 ms	1RM BS and RFD 0–50 ms: $r = 0.63$ (Pre), $r = 0.44$ (Post); 0–100 ms: $r = 0.70$ (Pre), $r = 0.65$ (Post); 0–150 ms: $r = 0.71$ (Pre), $r = 0.70$ (Post); 0–200 ms: $r = 0.59$ (Pre), $r = 0.69$ (Post); 0–250 ms: $r = 0.58$ (Pre), $r = 0.69$ (Post) 1RM HPC and RFD 0–50 ms: $r = 0.76$ (Pre), $r = 0.62$ (Post); 0–100 ms: $r = 0.77$ (Pre), $r = 0.77$ (Post); 0–150 ms: $r = 0.76$ (Pre), $r = 0.73$ (Post); 0–200 ms: $r = 0.64$ (Pre), $r = 0.71$ (Post); 0–250 ms: $r = 0.58$ (Pre), $r = 0.62$ (Post) Isometric leg press and RFD 0–50 ms: $r = 0.34$ (Pre), $r = 0.38$ (Post); 0–100 ms: $r = 0.59$ (Pre), $r = 0.72$ (Post); 0–150 ms: $r = 0.72$ (Pre), $r = 0.83$ (Post); 0–200 ms: $r = 0.73$ (Pre), $r = 0.86$ (Post); 0–250 ms: $r = 0.74$ (Pre), $r = 0.90$ (Post)

1RM one repetition maximum, *BS* back squat, *CMJ* countermovement jump, *HPC* hang power clean, *IMTP* isometric mid-thigh clean pull, *IMTPa* allometrically-scaled isometric mid-thigh clean pull, *IRFD* isometric rate of force development, *IS* isometric squat, *MVC* maximal voluntary contraction, *Rel* relative, per kilogram of body mass, *RFD* rate of force development, *SJ* squat jump

has compared RFD values between stronger and weaker individuals. However, two of the previous studies indicated that stronger individuals produce greater RFD compared to those who are weaker [34, 38], while one study indicated that there was no statistical difference between the strongest and weakest individuals tested [37]. However, magnitude-based inferences from the latter study would indicate that there was a very large practical difference in RFD (Cohen's $d = 23.5$). Possible explanations for the lack of statistical differences between stronger and weaker groups in the latter study may be the small sample size in each group ($n = 6$) and the range in subject abilities within each group (e.g. Olympic training site cyclists and local cyclists).

3.2 External Mechanical Power

Previous research has indicated that external mechanical power may be the determining factor that differentiates the performance between athletes in sports [4, 40–51]. External mechanical power of the system reflects the sum of joint powers and may represent the coordinated effort of the lower body [52]. Therefore, instead of the sum of joint powers, system external mechanical power is often measured and has been related to a number of different sport performance characteristics such as sprinting [53, 54], jumping [55–58], change of direction [42, 59, 60], and throwing velocity [61, 62]. As a result, many have suggested that external mechanical power is one of the most important characteristics with regard to performance [4–6]. In fact, previous research has indicated that there were performance differences in external mechanical power between the playing level of athletes [10, 15, 18] and between starters and non-starters [7, 9–12]. As a result, it is not surprising that practitioners often seek to develop and improve external mechanical power in an effort to translate to improved sport performance.

Partly based on the concepts of Minetti [63] and Zamparo et al. [64], a periodization model has been developed termed phase potentiation [65, 66]. The idea behind this model is that the previous phase of training will potentiate or enhance the ability to realize specific physiological characteristics in a subsequent phase of training [67, 68]. For example, the completion of a strength-endurance phase, where the primary goals are to increase muscle cross-sectional area and work capacity, would enhance the ability to realize muscular strength characteristics in a maximal strength phase and a maximal strength phase would enhance the ability to realize muscular power characteristics in a subsequent strength-power or explosive speed phase of training. Taking the above into account, it would be logical that greater muscular strength would ultimately contribute to the ability to realize greater net joint power characteristics. A number of studies have indicated that the completion of strength training programs leads to an increase in absolute or relative external mechanical power [27, 51, 69–79]. The effectiveness of strength training programs may be explained by Newton's second law of motion (Σ forces acting on an object = object's mass • Object's acceleration). Within this law, the change in motion of an object (i.e. acceleration) is directly proportional to the forces impressed upon it. If greater forces are produced over a given period of time, a greater acceleration is produced, resulting in a greater velocity. Thus, increases in both force and velocity will ultimately result in an increase in power. Given that muscular strength has been defined as the ability to exert force on an external object or resistance [1, 2], practitioners must consider the importance of enhancing maximal strength when it comes to the development and improvement of external mechanical power. Previous research has examined the relationships between an individual's strength levels and external mechanical power (Table 2).

Collectively, the studies displayed in Table 2 reported 177 Pearson correlation coefficients. 134 of the reported correlation magnitudes (76 %) displayed moderate or greater relationship with strength, while 116 (65 %) displayed a correlation magnitude of greater than or equal to 0.5, indicating a large relationship. In support of these findings, several studies have examined external mechanical power performance differences between stronger and weaker subjects. Many of the studies indicated that the stronger subjects produced statistically greater external mechanical power characteristics as compared to their weaker counterparts [12, 14, 15, 37, 48, 55, 56, 85, 87–95], while only one study noted that no statistical differences existed between strong and weak subjects [38]. However, the authors of the latter article noted that the lack of statistical differences between strong and weak subjects may have been due to the lack of task homogeneity of the examined subjects which included cricket, judo, rugby, and soccer athletes. A second potential explanation may be the use of an isometric strength test compared to a dynamic strength test. The authors of the latter study indicated that dynamic strength tests may be more practical when assessing relationships between relative strength and dynamic performance. For a more detailed comparison, readers are directed to a review by Cormie and colleagues [96]. Taken collectively, the scientific literature suggests that muscular strength is highly correlated to external mechanical power and may be considered the foundation upon which external mechanical power can be built [25, 97, 98].

4 Influence of Strength on General Sport Skills

Some of the most common movements in sports are jumping, sprinting, and rapid change of direction (COD) tasks. The ability to perform these movements effectively may ultimately determine the outcome of certain events. As discussed previously, muscular strength can have a significant influence on important force-time characteristics related to performance. In theory, enhanced force-time characteristics should transfer to the ability to perform general sport skills. Therefore, the influence of muscular strength on jumping, sprinting, and COD cannot be overlooked.

4.1 Jumping

Jumping tasks, whether they are vertical or horizontal, are regularly performed and are often part of a larger skill set needed to be successful in sport competitions. In some instances, the ability to jump higher or farther than another competitor will determine who wins the competition (e.g., high jump, long jump, triple jump), while the repetitive nature of jumping tasks in other sports does not determine the winner. In team sports, jumping tasks may be used during rebounding in basketball, spiking/blocking in volleyball, diving in baseball, etc. While impulse may ultimately determine the jumping performance of an individual [21], distinct force-time characteristics may determine the shape and magnitude of the impulse created [99, 100]. As noted above, greater muscular strength may modify the force-time characteristics of an individual. Specifically, increases in muscular strength achieved through resistance training can alter both peak performance variables as well as the shape of the force-time curve [77, 89, 101]. Further research has indicated that stronger individuals may possess distinct force-time curve characteristics compared to weaker individuals (e.g., unweighted phase duration, relative shape of the jump phases, net impulse forces) [55, 77, 99]. Specifically, stronger subjects produced a shorter unweighted phase [99] and greater forces in the area of the force-time curve corresponding to net impulse compared to weaker subjects [55]. Moreover, increases in maximal strength following 10 weeks of strength training produced positive force adaptations during the late eccentric/early concentric phase of jump squats [77]. In support of previous research, a number of other studies examined the relationships between maximal strength and jumping performance (Table 3).

Collectively, the studies displayed in Table 3 reported 116 Pearson correlation magnitudes. Ninety-one of the reported correlation magnitudes (78 %) displayed a moderate or greater relationship with strength. Furthermore, 69

Table 2 Summary of studies correlating maximal strength and peak power variables

Study	Subjects (*n*)	Strength measure	PP measure	Correlation results
Baker and Nance [49]	Professional male rugby league players ($n = 20$)	3RM BS, 3RM BP, 3RM HPC	JS, incline BP throw	JS: $r = 0.81$ (3RM BS), $r = 0.79$ (3RM HPC) Incline BP throw: $r = 0.89$ (3RM BP), $r = 0.55$ (3RM HPC)
Baker [15]	National Rugby League and city-league college-aged rugby league males ($n = 49$)	1RM BP	BP throw at PP load	$r = 0.82$ (All), $r = 0.58$ (National Rugby League players), $r = 0.85$ (City-league players)
Baker et al. [80]	Professional and semiprofessionals male rugby league players ($n = 31$)	1RM BP	BP throw at PP load	$r = 0.66$ (Professional), $r = 0.85$ (Semiprofessional)
Carlock et al. [44]	National-level male and female junior and senior weightlifters ($n = 64$)	1RM BS, 1RM snatch, 1RM CandJ, Rel 1RM BS, Rel 1RM snatch, Rel 1RM CandJ	CMJ and SJ PP, Rel PP	1RM BS and CMJ PP: $r = 0.91$ (Men), 0.82 (Women), 0.92 (All); Rel CMJ PP: $r = -0.17$ (Men), 0.23 (Women), 0.39 (All); SJ PP: $r = 0.91$ (Men), 0.82 (Women), 0.93 (All); Rel SJ PP: $r = 0.42$ (Men), 0.33 (Women), 0.42 (All) 1RM Snatch and CMJ PP: $r = 0.93$ (Men), 0.76 (Women), 0.93 (All); Rel CMJ PP: $r = -0.10$ (Men), 0.15 (Women), 0.47 (All); SJ PP: $r = 0.93$ (Men), 0.76 (Women), 0.92 (All); Rel SJ PP: $r = 0.23$ (Men), 0.28 (Women), 0.60 (All) 1RM C&J and CMJ PP: $r = 0.90$ (Men), 0.76 (Women), 0.91 (All); Rel CMJ PP: $r = -0.19$ (Men), 0.17 (Women), 0.45 (All); SJ PP: $r = 0.90$ (Men), 0.76 (Women), 0.90 (All); Rel SJ PP: $r = 0.34$ (Men), 0.26 (Women), 0.59 (All) Rel 1RM BS: $r = 0.29$ (CMJ PP), $r = 0.49$ (Rel CMJ PP), $r = 0.24$ (SJ PP), $r = 0.72$ (Rel SJ PP) Rel 1RM Snatch: $r = 0.25$ (CMJ PP), $r = 0.53$ (Rel CMJ PP), $r = 0.20$ (SJ PP), $r = 0.74$ (Rel SJ PP) Rel 1RM C&J: $r = 0.19$ (CMJ PP), $r = 0.71$ (Rel CMJ PP), $r = 0.14$ (SJ PP), $r = 0.71$ (Rel SJ PP)
Cronin and Hansen [81]	Professional male rugby league players ($n = 16$)	3RM BS	30 kg JS average power, Rel 30 kg JS average power	$r = 0.42$ (JS average power), $r = 0.15$ (Rel 30 kg JS average power)
Haff et al. [31]	Elite female weightlifters ($n = 6$)	IMTP	CMJ, SJ PP	$r = 0.88$ (CMJ) $r = 0.92$ (SJ)
Jones et al. [82]	Recreationally-trained males ($n = 29$)	1RM BS	CMJ PP, average power	$r = 0.70$ (PP), $r = 0.67$ (Average power)
Kawamori et al. [32]	Collegiate male athletes ($n = 15$)	1RM HPC, Rel 1RM HPC	CMJ and SJ PP	1RM HPC: $r = 0.68$ (CMJ), $r = 0.71$ (SJ) Rel 1RM HPC: $r = 0.45$ (CMJ), $r = 0.46$ (SJ)
Kawamori et al. [33]	Collegiate male weightlifters ($n = 8$)	IMTP	CMJ, SJ PP	$r = 0.95$ (CMJ), $r = 0.70$ (SJ)
Moss et al. [51]	Well-trained male physical education students ($n = 30$)	1RM Elbow flexion	Elbow flexion PP, elbow flexion with 2.5 kg PP	$r = 0.93$ (Elbow flexion PP), $r = 0.73$ (Elbow flexion with 2.5 kg)

Table 2 continued

Study	Subjects (n)	Strength measure	PP measure	Correlation results
Nuzzo et al. [46]	Male NCAA division I AA football and track and field athletes ($n = 12$)	1RM BS, 1RM PC, IS (140° knee angle), IMTP, Rel 1RM BS, Rel 1RM PC, Rel IS, Rel IMTP	CMJ PP, Rel CMJ PP	PP: $r = 0.84$ (1RM BS), $r = 0.86$ (1RM PC), $r = 0.71$ (IS), $r = 0.75$ (IMTP) Rel PP: $r = 0.68$ (Rel 1RM BS), $r = 0.71$ (Rel 1RM PC), $r = 0.27$ (Rel IS), $r = 0.51$ (Rel IMTP)
Peterson et al. [83]	First-year male and female collegiate athletes ($n = 55$)	1RM BS, Rel 1RM BS	CMJ PP	1RM BS: $r = 0.92$ (All), $r = 0.66$ (Males), $r = 0.72$ (Females) Rel 1RM BS: $r = 0.69$ (All), $r = 0.39$ (Males), $r = -0.06$ (Females)
Requena et al. [84]	Professional male soccer players ($n = 21$)	1RM COHS, knee extensor MVC, plantar flexor MVC	COHS PP with 50, 75, 100, and 125 % of BM loads	50 % BM PP: $r = 0.59$ (1RM COHS), $r = 0.60$ (Knee Extensor MVC), $r = 0.61$ (Plantar Flexor MVC) 75 % BM PP: $r = 0.66$ (1RM COHS), $r = 0.65$ (Knee Extensor MVC), $r = 0.49$ (Plantar Flexor MVC) 100 % BM PP: $r = 0.83$ (1RM COHS), $r = 0.67$ (Knee Extensor MVC), $r = 0.57$ (Plantar Flexor MVC) 125 % BM PP: $r = 0.75$ (1RM COHS), $r = 0.58$ (Knee Extensor MVC), $r = 0.39$ (Plantar Flexor MVC)
Sheppard et al. [85]	International-level male volleyball players ($n = 21$)	Rel 1RM BS, Rel 1RM PC	CMJ Rel PP, CMJ +50 % body mass Rel PP	CMJ Rel PP: $r = 0.52$ (Rel 1RM BS), $r = 0.50$ (Rel 1RM PC) CMJ +50 % body mass Rel PP: $r = 0.59$ (Rel 1RM BS), $r = 0.51$ (Rel 1RM PC)
Speranza et al. [86]	Male first grade ($n = 10$), second grade ($n = 12$), and under 20 s ($n = 14$) semi-professional rugby league players	3RM BS, Rel 3RM BS	CMJ PP	3RM BS: $r = 0.44$ (All), $r = 0.57$ (First grade), $r = 0.35$ (Second grade), $r = 0.36$ (Under 20 s) Rel 3RM BS: $r = 0.11$ (All), $r = 0.38$ (First grade), $r = 0.10$ (Second grade), $r = -0.02$ (Under 20 s)
Speranza et al. [86]	Male first grade ($n = 10$), second grade ($n = 12$), and under 20 s ($n = 14$) semi-professional rugby league players	3RM BP, Rel 3RM BP	Plyometric push-up PP	3RM BP: $r = 0.43$ (All), $r = 0.79$ (First grade), $r = 0.07$ (Second grade), $r = 0.55$ (Under 20 s) Rel 3RM BP: $r = 0.09$ (All), $r = 0.02$ (First grade), $r = 0.30$ (Second grade), $r = -0.18$ (Under 20 s)
Stone et al. [48]	Males with BS experience ranging 7 weeks – 15 + years ($n = 22$)	1RM BS	CMJ, SJ at 10–100 % 1RM BS	CMJ: $r = 0.78$ (10 %), $r = 0.84$ (20 %), $r = 0.85$ (30 %), $r = 0.88$ (40 %), $r = 0.88$ (50 %), $r = 0.85$ (60 %), $r = 0.84$ (70 %), $r = 0.80$ (80 %), $r = 0.73$ (90 %), $r = 0.60$ (100 %) SJ: $r = 0.84$ (10 %), $r = 0.87$ (20 %), $r = 0.90$ (30 %), $r = 0.94$ (40 %), $r = 0.94$ (50 %), $r = 0.93$ (60 %), $r = 0.90$ (70 %), $r = 0.91$ (80 %), $r = 0.86$ (90 %), $r = 0.75$ (100 %)
Stone et al. [37]	International and local-level male cyclists ($n = 30$)	IMTP, Rel IMTP, IMTPa	CMJ and SJ PP, Rel PP, PPa	IMTP: $r = 0.79$ (CMJ PP), $r = 0.49$ (CMJ Rel PP), $r = 0.67$ (CMJ PPa), $r = 0.78$ (SJ PP), $r = 0.42$ (SJ Rel PP), $r = 0.62$ (SJ PPa) Rel IMTP: $r = 0.40$ (CMJ PP), $r = 0.43$ (CMJ Rel PP), $r = 0.44$ (CMJ PPa), $r = 0.39$ (SJ PP), $r = 0.40$ (SJ Rel PP), $r = 0.42$ (SJ PPa) IMTPa: $r = 0.60$ (CMJ PP), $r = 0.48$ (CMJ Rel PP), $r = 0.57$ (CMJ PPa), $r = 0.59$ (SJ PP), $r = 0.43$ (SJ Rel PP), $r = 0.54$ (SJ PPa)

Table 2 continued

Study	Subjects (*n*)	Strength measure	PP measure	Correlation results
Stone et al. [37]	National-level male and female cyclists ($n = 20$)	IMTP, Rel IMTP, IMTPa	CMJ and SJ PP, Rel PP, PPa	IMTP: $r = 0.85$ (CMJ PP), $r = 0.68$ (CMJ Rel PP), $r = 0.78$ (CMJ PPa), $r = 0.86$ (SJ PP), $r = 0.69$ (SJ Rel PP), $r = 0.78$ (SJ PPa) Rel IMTP: $r = 0.41$ (CMJ PP), $r = 0.56$ (CMJ Rel PP), $r = 0.52$ (CMJ PPa), $r = 0.42$ (SJ PP), $r = 0.62$ (SJ Rel PP), $r = 0.56$ (SJ PPa) IMTPa: $r = 0.64$ (CMJ PP), $r = 0.68$ (CMJ Rel PP), $r = 0.73$ (CMJ PPa), $r = 0.61$ (SJ PP), $r = 0.72$ (SJ Rel PP), $r = 0.76$ (SJ PPa)
Thomas et al. [38]	Male collegiate cricket, judo, rugby, and soccer athletes ($n = 22$)	IMTP, Rel IMTP	CMJ, SJ PP	IMTP: $r = 0.34$ (CMJ), $r = 0.46$ (SJ) Rel IMTP: $r = 0.01$, $r = 0.15$ (SJ)

1RM one repetition maximum, *3RM* three repetition maximum, *BP* bench press, *BS* back squat, *C&J* clean and jerk, *CMJ* countermovement jump, *COHS* concentric-only half-squat, *HPC* hang power clean, *IMTP* isometric mid-thigh clean pull, *IMTPa* allometrically-scaled isometric mid-thigh clean pull, *IS* isometric squat, *JS* jump squat, *MVC* maximal voluntary contraction, *PC* power clean, *PP* peak power, *PPa* allometrically-scaled peak power, *Rel* relative, per kilogram of body mass, *SJ* squat jump

correlation magnitudes (59 %) were greater than or equal to 0.5, indicating a large relationship. In support of these findings, several studies indicated that stronger individuals jumped higher compared to weaker individuals [12, 34, 50, 56, 85]. In contrast, one study indicated that there was no difference in jump height between strong and weak subjects [38]. A potential explanation for the latter findings may include the lack of task homogeneity of the subjects and the use of an isometric strength test compared to a dynamic strength test to compare dynamic performance.

4.2 Sprinting

The ability to accelerate rapidly and reach high sprinting speeds is a vital component of many sports or events. While peak sprinting speeds may dictate the winner of certain track events (e.g., 100, 200 m, etc.), athletes playing field sports such as soccer, rugby, lacrosse, and field hockey may not necessarily reach their maximum velocity regularly [113]. In fact, the average sprint time in soccer [114] and rugby union [115] is approximately 2 s covering distances of about 14 m [116] and 20 m [117, 118], respectively. Further research indicated that rugby union players may only reach approximately 70 % of their maximum sprinting speed after sprinting for 2 s [119]. Thus, it would appear that the ability to accelerate over short distances may be paramount for field athletes.

Previous research indicated that elite athletes produced greater speeds over short distances compared to non-elite athletes [120]. Faster runners possess several characteristics such as greater force application, shorter ground contact times, and greater stride lengths [54]. Further research indicated that sprint performance may be limited by the ability to produce a high RFD over the brief contacts instead of the ability to apply force [53]. In fact, better sprinters are able to generate greater vertical forces within the first half of their stance phase [16]. As displayed above, maximal strength is strongly correlated with RFD and thus, it is logical that sprinting performance would also be related to the strength level of individuals. Previous research has indicated that increases in strength coincide with increases in short sprint performance [121–125]. In support of these findings, a number of studies have examined the relationships between maximal strength and sprinting performance (Table 4).

Better sprinting performances are indicated by faster sprint times and higher speeds. Collectively, 67 correlation magnitudes between strength and sprinting performance were reported in Table 4. Of those within the table, 57 reported a moderate or greater relationship with strength (85 %), while 44 (66 %) displayed substantial relationships with strength. The correlation results presented in Table 4 are supported by a recent meta-analysis that indicated that

Table 3 Summary of studies correlating maximal strength and jump height/distance

Study	Subjects (n)	Strength measure	Jump type	Correlation results
Augustsson and Thomeé [102]	Recreationally-trained males ($n = 16$)	3RM BS	CMJ	$r = 0.51$
Blackburn et al. [45]	Healthy female college students ($n = 20$)	1RM BS, 1RM knee extension	CMJ, broad jump	1RM BS: $r = 0.65$ (CMJ), $r = 0.72$ (Broad jump) 1RM Knee extension: $r = 0.10$ (CMJ), 0.07 (Broad jump)
Carlock et al. [44]	National-level male and female junior and senior weightlifters ($n = 64$)	1RM BS, 1RM snatch, 1RM CandJ, Rel 1RM BS, Rel 1RM snatch, Rel 1RM CandJ	CMJ, SJ	CMJ: $r = 0.52$ (1RM BS), $r = 0.60$ (1RM Snatch), $r = 0.59$ (1RM CandJ), $r = 0.69$ (Rel 1RM BS), $r = 0.76$ (Rel 1RM Snatch), $r = 0.72$ (Rel 1RM CandJ) SJ: $r = 0.58$ (1RM BS), $r = 0.64$ (1RM Snatch), $r = 0.64$ (1RM C&J), $r = 0.72$ (Rel 1RM BS), $r = 0.75$ (Rel 1RM Snatch), $r = 0.72$ (Rel 1RM C&J)
Comfort et al. [103]	Well-trained youth male soccer players ($n = 34$)	1RM BS, Rel 1RM BS	CMJ, SJ	1RM BS: $r = 0.76$ (CMJ), $r = 0.76$ (SJ) Rel 1RM BS: $r = 0.62$ (CMJ), $r = 0.64$ (SJ)
Cronin and Hansen [81]	Professional male rugby league players ($n = 16$)	3RM BS	CMJ, 30 kg JS	$r = 0.14$ (CMJ), $r = 0.16$ (30 kg JS)
Jones et al. [82]	Recreationally-trained males ($n = 29$)	1RM BS	CMJ, broad jump	$r = 0.22$ (CMJ), $r = 0.17$ (Broad jump)
Kawamori et al. [32]	Collegiate male athletes ($n = 15$)	1RM HPC, Rel 1RM HPC	CMJ, SJ	1RM HPC: $r = 0.13$ (CMJ), $r = 0.09$ (SJ) Rel 1RM HPC: $r = 0.56$ (CMJ), $r = 0.47$ (SJ)
Kawamori et al. [33]	Collegiate male weightlifters ($n = 8$)	IMTP	CMJ, SJ	$r = 0.82$ (CMJ), $r = 0.87$ (SJ)
Koch et al. [104]	Male and female track and field athletes ($n = 11$) Untrained male and female subjects ($n = 21$)	1RM BS	Broad jump	$r = 0.81$
Kraska et al. [34]	Male and female NCAA division I athletes ($n = 81$)	IMTP, IMTPa	CMJ, SJ LCMJ, LSJ	IMTP: $r = 0.36$ (CMJ) $r = 0.40$ (SJ), $r = 0.55$ (LCMJ), $r = 0.55$ (LSJ) IMTPa: $r = 0.41$ (CMJ) $r = 0.41$ (SJ), $r = 0.52$ (LCMJ), $r = 0.52$ (LSJ)
Loturco et al. [105]	Male and female Brazilian national team boxers ($n = 15$)	IS (90° knee angle)	CMJ, SJ	$r = 0.79$ (CMJ), $r = 0.79$ (SJ)
McGuigan et al. [35]	NCAA division III male wrestlers ($n = 8$)	IMTP	CMJ	$r =$ Not specified
McGuigan and Winchester [36]	NCAA division I male football players ($n = 22$)	1RM BS, IMTP	CMJ, broad jump	CMJ: $r = 0.54$ (1RM BS), Not specified for IMTP Broad jump: Not specified for 1RM BS or IMTP
McGuigan et al. [106]	Recreationally-trained males ($n = 26$)	1RM BS, IMTP, 1RM BP	CMJ	$r = 0.69$ (1RM BS), $r = 0.72$ (IMTP), $r = 0.70$ (1RM BP)

Table 3 continued

Study	Subjects (n)	Strength measure	Jump type	Correlation results
Nimphius et al. [42]	Female Australian Institute of Sport state softball players ($n = 10$)	Rel 1RM BS	CMJ	$r = 0.36$ (Pre-season), $r = 0.38$ (Mid-season), $r = 0.16$ (Post-season)
Nuzzo et al. [46]	Male NCAA division I AA football and track and field athletes ($n = 12$)	1RM BS, 1RM PC, IS (140° knee angle), IMTP, Rel 1RM BS, Rel 1RM PC, Rel IS, Rel IMTP	CMJ	$r = 0.22$ (1RM BS), $r = 0.06$ (1RM PC), $r = -0.07$ (IS), $r = 0.28$ (IMTP), $r = 0.69$ (Rel 1RM BS), $r = 0.64$ (Rel 1RM PC), $r = 0.28$ (Rel IS), $r = 0.59$ (Rel IMTP)
Peterson et al. [83]	First-year male and female collegiate athletes ($n = 55$)	1RM BS, Rel 1RM BS	CMJ, broad jump	1RM BS and CMJ: $r = 0.86$ (All), $r = 0.54$ (Males), $r = 0.37$ (Females); Broad jump: $r = 0.77$ (All), $r = 0.45$ (Males), $r = 0.31$ (Females) Rel 1RM BS and CMJ: $r = 0.85$ (All), $r = 0.67$ (Males), $r = 0.55$ (Females); Broad jump: $r = 0.81$ (All), $r = 0.53$ (Males), $r = 0.64$ (Females)
Requena et al. [84]	Professional male soccer players ($n = 21$)	1RM COHS, knee extensor MVC, plantar flexor MVC	CMJ, SJ	CMJ: $r = 0.50$ (1RM COHS), $r = 0.57$ (Knee Extensor MVC), $r = 0.14$ (Plantar Flexor MVC) SJ: $r = 0.50$ (1RM COHS), $r = 0.55$ (Knee Extensor MVC), $r = 0.30$ (Plantar Flexor MVC)
Secomb et al. [107]	International-level male surfers ($n = 15$)	IMTP	CMJ, SJ	$r = 0.65$ (CMJ), $r = 0.58$ (SJ)
Secomb et al. [108]	Junior male and female competitive surfers ($n = 30$)	IMTP, Rel IMTP	CMJ, SJ	IMTP: $r = 0.48$ (CMJ), $r = 0.48$ (SJ) Rel IMTP: $r = 0.46$, $r = 0.40$ (SJ)
Sheppard et al. [85]	International-level male volleyball players ($n = 21$)	Rel 1RM BS, Rel 1RM PC	CMJ, Rel CMJ, spike jump, Rel spike jump, DJ, Rel DJ	CMJ: $r = -0.44$ (Rel 1RM BS), $r = -0.40$ (Rel 1RM PC) Rel CMJ: $r = 0.54$ (Rel 1RM BS), $r = 0.53$ (Rel 1RM PC) Spike jump: $r = -0.06$ (Rel 1RM BS), $r = -0.01$ (Rel 1RM PC) Rel Spike jump: $r = 0.64$ (Rel 1RM BS), $r = 0.65$ (Rel 1RM PC) DJ: $r = -0.35$ (Rel 1RM BS), $r = -0.29$ (Rel 1RM PC) Rel DJ: $r = 0.55$ (Rel 1RM BS), $r = 0.55$ (Rel 1RM PC)
Stone et al. [37]	International and local-level male cyclists ($n = 30$)	IMTP, Rel IMTP, IMTPa	CMJ, SJ	IMTP: $r = 0.59$ (CMJ), $r = 0.51$ (SJ) Rel IMTP: $r = 0.45$ (CMJ), $r = 0.42$ (SJ) IMTPa: $r = 0.54$ (CMJ), $r = 0.48$ (SJ)
Stone et al. [37]	National-level male and female cyclists ($n = 20$)	IMTP, Rel IMTP, IMTPa	CMJ, SJ	IMTP: $r = 0.67$ (CMJ), $r = 0.66$ (SJ) Rel IMTP: $r = 0.59$ (CMJ), $r = 0.61$ (SJ) IMTPa: $r = 0.67$ (CMJ), $r = 0.68$ (SJ)
Thomas et al. [38]	Male collegiate cricket, judo, rugby, and soccer athletes ($n = 22$)	IMTP, Rel IMTP	CMJ, SJ	IMTP: $r = -0.02$ (CMJ), $r = -0.04$ (SJ) Rel IMTP: $r = -0.09$, $r = -0.10$ (SJ)
Ugarkovic et al. [109]	Junior male basketball players ($n = 33$)	Rel hip extensor MVC, Rel knee extensor MVC	CMJ	$r = 0.38$ (Rel hip extensor MVC), $r = 0.52$ (Rel knee extensor MVC)
Wisløff et al. [110]	Norwegion elite male soccer players ($n = 29$)	1RM BS	CMJ	$r = 0.61$

Table 3 continued

Study	Subjects (*n*)	Strength measure	Jump type	Correlation results
Wisløff et al. [50]	International male soccer players ($n = 17$)	1RM HS	CMJ	$r = 0.78$
Yamauchi and Ishii [111]	Untrained men and women ($n = 67$)	Isometric knee-hip extension peak force on servo-controlled dynamometer, Rel peak force	CMJ	$r = 0.48$ (Peak force), $r = 0.24$ (Rel Peak force)
Young et al. [112]	Males with at least 1 year of jumping experience ($n = 29$)	Rel IS (120° knee angle)	CMJ, run-up jump	$r = 0.33$ (CMJ), $r = 0.33$ (Run-up jump)

1RM one repetition maximum; *3RM* three repetition maximum; *BP* bench press; *BS* back squat; *C&J* clean and jerk; *CMJ* countermovement jump; *COHS* concentric-only half-squat; *DJ* depth, drop jump; *HPC* hang power clean; *HS* half-squat; *IMTP* isometric mid-thigh clean pull; *IMTPa* allometrically-scaled isometric mid-thigh clean pull; *IS* isometric squat; *JS* jump squat; *PC* power clean; *Rel* relative, per kilogram of body mass; *SJ* squat jump

increases in lower body strength positively transfer to sprinting performance [134]. Further research indicated that stronger individuals produced faster sprinting performances compared to those who were weaker [50, 56, 81, 130, 131, 135], while some research indicated that there was no difference between strong and weak subjects [14, 81]. A potential explanation for the conflicting findings was the use of only absolute strength measures in both investigations [14, 81] without a report or analysis of relative strength and sprinting performance.

4.3 Change of Direction

For the purposes of this review, relationships between strength and COD performance were evaluated strictly on pre-planned COD tests because the neuromuscular strategies associated with agility (reactive) performance are unique and highly dependent on a combination of cognitive processing strategies [136]. Thus, this review focused on the relationship between the physical capacity of COD and the physical attribute of strength. However, future research should seek to understand the interaction between perceptual-cognitive strategies and the ability to use physical attributes such as strength during agility tasks as the most recent research indicates that direct relationships between strength and agility are only small in magnitude or do not differ between stronger and weaker athletes [137, 138]. Similar to sprinting, RFD is critical for COD tasks that occur in periods that preclude athletes from producing their maximal force capacity. Specifically, the plant phase, which is when the actual COD occurs, can range from 0.23–0.77 s dependent on the entry velocity and severity of the COD angle required [137, 139–141]. All ground contact lengths during a COD exceed the typical ground contact time of both the acceleration phase of sprinting (0.17–0.2 s) [142] and the maximal velocity phase of sprinting (0.09–0.11 s) [143]. Therefore a strong relationship between maximal strength and COD performance would be expected, as there is greater amount of time available to utilize one's maximal strength. However, similar to sprinting, COD performance requires not only having the strength to change one's momentum, but also the ability to use this strength through coordinated body movements within the constraints of the activity [136, 137, 139, 144, 145].

Based upon mathematical principles, those that can apply greater force over a given time (greater impulse) should be able to accelerate or change momentum with the fastest velocity. However, the disparity in the expected magnitude of the relationship between strength and COD may have more to do with the tests used to measure "COD ability" and "strength" rather than the lack of association between strength and COD ability. This hypothesis is supported by research questioning the validity of "total time" in the assessment of COD ability and that smaller

Table 4 Summary of studies correlating maximal strength and sprinting performance variables

Study	Subjects (n)	Strength measure	Sprint measure	Correlation results
Baker and Nance [126]	Professional male rugby league players ($n = 20$)	3RM BS, 3RM HPC, Rel 3RM BS, Rel 3RM HPC	10, 40 m times	10 m: $r = -0.06$ (3RM BS), $r = -0.36$ (3RM HPC), $r = -0.39$ (Rel 3RM BS), $r = -0.56$ (Rel 3RM PC) 40 m: $r = -0.19$ (3RM BS), $r = -0.24$ (3RM HPC), $r = -0.66$ (Rel 3RM BS), $r = -0.72$ (Rel 3RM PC)
Chaouachi et al. [127]	Tunisian national team male basketball players ($n = 14$)	1RM HS	5, 10, 30 m times	$r = -0.63$ (5 m), $r = -0.68$ (10 m), $r = -0.65$ (30 m)
Comfort et al. [103]	Well-trained youth male soccer players ($n = 34$)	1RM BS, Rel 1RM BS	5, 20 m times	1RM BS: $r = -0.60$ (5 m), $r = -0.65$ (20 m) Rel 1RM BS: $r = -0.52$ (5 m), $r = -0.67$ (20 m)
Cronin and Hansen [81]	Professional male rugby league players ($n = 16$)	3RM BS	5, 10, 30 m times	$r = -0.05$ (5 m), $r = -0.01$ (10 m), $r = -0.29$ (30 m)
Harris et al. [128]	Male national-level rugby training squad and national rugby league premier squad members ($n = 30$)	1RM machine hack squat, Rel 1RM machine hack squat	10, 30/40 m times	10 m: $r = 0.20$ (1RM), $r = -0.10$ (Rel 1RM) 30/40 m: $r = -0.14$ (1RM), $r = -0.33$ (Rel 1RM)
Lockie et al. [129]	Male field sport athletes ($n = 20$)	3RM BS, Rel 3RM BS	0–5, 5–10, and 0–10 m velocity	3RM BS: $r = 0.43$ (0–5 m), $r = 0.60$ (5–10 m), $r = 0.47$ (0–10 m) Rel 3RM BS: $r = 0.50$ (0–5 m), $r = 0.66$ (5–10 m), $r = 0.56$ (0–10 m)
McBride et al. [130]	NCAA division I AA football players ($n = 17$)	Rel 1RM BS	5, 10, 40 m times	$r = -0.45$ (5 m), $r = -0.54$ (10 m), $r = -0.60$ (40 m)
Meckel et al. [131]	NCAA division I female track field sprinters ($n = 30$)	Rel 1RM BS	100 m	$r = -0.89$
Nimphius et al. [42]	Female Australian Institute of Sport state softball players ($n = 10$)	Rel 1RM BS	10 m split to first base, first base, Second base times	10 m split: $r = -0.87$ (Pre-season), $r = -0.85$ (Mid-season), $r = -0.75$ (Post-season) First base: $r = -0.84$ (Pre-season), $r = -0.84$ (Mid-season), $r = -0.80$ (Post-season) Second base: $r = -0.84$ (Pre-season), $r = -0.79$ (Mid-season), $r = -0.83$ (Post-season)
Peterson et al. [83]	First-year male and female collegiate athletes ($n = 55$)	1RM BS, Rel 1RM BS	20, 40 y velocities	1RM BS and 20y: $r = 0.82$ (All), $r = 0.39$ (Males), $r = 0.38$ (Females); 40y: $r = 0.85$ (All), $r = 0.43$ (Males), $r = 0.40$ (Females) Rel 1RM BS and 20y: $r = 0.88$ (All), $r = 0.65$ (Males), $r = 0.72$ (Females); 40y: $r = 0.88$ (All), $r = 0.72$ (Males), $r = 0.71$ (Females)
Requena et al. [84]	Professional male soccer players ($n = 21$)	1RM COHS, knee extensor MVC, plantar flexor MVC	15 m time	$r = -0.47$ (1RM COHS), $r = -0.42$ (Knee Extensor MVC), $r = -0.35$ (Plantar Flexor MVC)
Seitz et al. [132]	Male junior rugby league players ($n = 13$)	1RM BS, Rel 1RM BS, 1RM PC, Rel 1RM PC	20 m time	$r = -0.60$ (1RM BS), $r = -0.57$ (Rel 1RM BS), $r = -0.62$ (1RM PC), $r = -0.64$ (Rel 1RM PC)

Table 4 continued

Study	Subjects (*n*)	Strength measure	Sprint measure	Correlation results
Thomas et al. [133]	Collegiate male soccer and rugby league players ($n = 14$)	IMTP	5, 20 m times	$r = -0.57$ (5 m), $r = -0.69$ (20 m)
Wisløff et al. [50]	International male soccer players ($n = 17$)	1RM HS	10, 30 m times	$r = -0.94$ (10 m), $r = -0.71$ (30 m)
Young et al. [113]	Australian junior national track and field hurdlers, jumpers, and multi-event athletes ($n = 7$)	IS (120° knee angle)	2.5, 10 m at max speed times	$r = -0.72$ (2.5 m), $r = -0.79$ (10 m at max speed)

1RM one repetition maximum, *3RM* three repetition maximum, *BP* bench press, *BS* back squat, *COHS* concentric-only half-squat, *HPC* hang power clean, *HS* half-squat, *IMTP* isometric mid-thigh clean pull, *IS* isometric squat, *MVC* maximal voluntary contraction, *PC* power clean, *Rel* relative, per kilogram of body mass

time intervals [146–148] or direct measures of center of mass velocity [144, 149] provide more valid assessments of COD ability that may ultimately assist in better understanding the underpinning relationship between strength and COD ability. With respect to the measurement of strength, recent research has shown that measures of eccentric, concentric, dynamic, and isometric strength all contribute to COD performance [150]; however, a majority of research simply measures one "type" of strength. When assessing COD performance by the 505 and T-test which require demanding COD (greater than 75°), eccentric strength contributed the most to COD performance [150]. Therefore, our understanding of the association between strength and COD ability are ever-expanding as we examine more specific or valid measures of each underpinning physical quality. Table 5 displays studies that have examined the relationships between maximal strength and COD performance.

Collectively, the studies displayed in Table 5 reported 45 Pearson correlation coefficients between COD performances (examined by a variety of running based tests) and maximal strength (using a variety of multi-joint assessments). Thirty-five of the correlation magnitudes (78 %) indicated a moderate or greater relationship with strength while 27 (60 %) displayed a large or greater relationship with strength. Previous research that has examined the differences in COD time between stronger and weaker subjects has been mixed [56, 137, 138, 144]. Some studies indicated that individuals who are faster during a COD test possess greater strength compared to those who are slower [137, 138]. Other research indicated that there was no difference between stronger and weaker subjects when total time was assessed [56, 144]. The difference in findings may be attributed to the sensitivity of the measure used to assess COD performance. For example, when COD performance was evaluated by total time to complete a COD task and the exit velocity out of a COD task (a measure specifically evaluating the change of direction step), only exit velocity was significantly faster in the stronger subjects [144]. Overall, a majority of the evidence supports a moderate to very large relationship between maximal strength and COD performance, but the limitations or variety of testing methodologies may primarily explain the various magnitudes of the relationships.

5 Influence of Strength on Specific Sport Skills and Performance

While the transfer of strength to the improvement of force-time characteristics is viewed as a positive adaptation from a theoretical standpoint, the transfer of strength to the actual sport skills and performance of athletes is

Table 5 Summary of studies correlating maximal strength and change of direction variables

Study	Subjects (n)	Strength test	COD test	Correlation results
Chaouachi et al. [127]	Tunisian national team male basketball players ($n = 14$)	1RM HS	T-test	$r = 0.18$
Delaney et al. [151]	Professional rugby league players ($n = 31$)	3RM BS, Rel 3RM BS	505-D time, 505-ND time,	3RM BS: $r = -0.28$ (505-D), $r = -0.21$ (505-ND) Rel 3RM BS: $r = -0.52$ (505-D), $r = -0.56$ (505-ND)
Hori et al. [56]	Semiprofessional male Australian rules football players ($n = 29$)	1RM FS, Rel 1RM FS	modified 505 time	1RM FS: $r = -0.37$ Rel 1RM FS: $r = -0.51$
Jones et al. [152]	University students (mixed gender) with various recreational sporting backgrounds ($n = 38$)	Rel 1RM leg press	505 time	$r = -0.45$
Markovic [153]	Male physical education students ($n = 76$)	1RM BS, IS (120° knee angle)	20-yard shuttle run time, slalom run time	1RM BS: $r = -0.31$ (20-yard shuttle run), $r = -0.21$ (Slalom run) IS: $r = 0.03$ (20-yard shuttle run), $r = 0.08$ (Slalom run)
Nimphius et al. [42]	Female West Australian Institute of Sport softball players ($n = 10$)	Rel 1RM BS	505-D time, 505-ND time	505-D: $r = -0.50$ (Pre-season), $r = -0.75$ (Mid-season), $r = -0.60$ (Post-season) 505-ND: $r = -0.75$ (Pre-season), $r = -0.73$ (Mid-season), $r = -0.85$ (Post-season)
Peterson et al. [83]	First-year male and female collegiate athletes ($n = 55$)	1RM BS, Rel 1RM BS	T-test time	1RM BS & T-test: $r = -0.78$ (All), $r = -0.17$ (Males), $r = -0.41$ (Females) Rel 1RM BS & T-test: $r = -0.81$ (All), $r = -0.33$ (Males), $r = -0.63$ (Females)
Spiteri et al. [150]	Female professional basketball players ($n = 12$)	Rel 1RM BS, Rel Con BS, Rel Ecc BS, Rel IMTP	505 time, T-test time	Rel 1RM BS: $r = -0.80$ (505), $r = -0.80$ (T-test), Rel Con BS: $r = -0.79$ (505), $r = -0.79$ (T-test) Rel Ecc BS: $r = -0.89$ (505), $r = -0.88$ (T-test) Rel IMTP: $r = -0.79$ (505), $r = -0.85$ (T-test)
Spiteri et al. [149]	Stronger ($n = 12$) and weaker ($n = 12$) recreational athletes; mixed gender	IS (unilateral)	45° COD task exit velocity, 45° COD task time	Exit Velocity - Stronger: $r = 0.89$ (force application during COD); $r = 0.95$ (impulse during COD); Weaker: $r = 0.52$ (force application during COD); $r = 0.13$ (impulse during COD) (Time) Stronger: $r = -0.37$ (force application during COD); $r = -0.48$ (impulse during COD); Weaker: $r = -0.32$ (force application during COD); $r = 0.17$ (impulse during COD)
Swinton et al. [154]	Scottish Premier League nonprofessional male rugby union players ($n = 30$)	ALLO 1RM BS, ALLO 1RM deadlift	505 time	ALLO 1RM BS: $r = -0.70$ ALLO 1RM Deadlift: $r = -0.72$
Thomas et al. [133]	Collegiate male soccer and rugby league players ($n = 14$)	IMTP	Modified 505 time	$r = -0.57$
Wisløff et al. [50]	International male soccer players ($n = 17$)	1RM HS	10 m shuttle run	$r = -0.68$

Table 5 continued

Study	Subjects (*n*)	Strength test	COD test	Correlation results
Young et al. [138]	Community-level male Australian rules football players ($n = 24$)	Rel 3RM HS	45° cut COD task time	$r = -0.20$

1RM one repetition maximum, *3RM* three repetition maximum, *505-D* 505 agility test performed with dominant leg, *505-ND* 505 agility test performed with non-dominant leg, *ALLO* allometrically-scaled, *BP* bench press, *BS* back squat, *COD* change of direction, *Con* concentric-only movement, *Ecc* eccentric-only movement, *FS* front squat, *HS* half-squat, *IMTP* isometric mid-thigh clean pull, *IS* isometric squat, *Rel* relative, per kilogram of body mass

paramount. If the strength characteristics of an athlete did not transfer to the performance of the athletes in their sports or events, sport coaches may be less inclined to incorporate resistance training as a method of preparing their athletes to perform. However, previous literature supports the notion that muscular strength is one of the underlying determinants of strength-power performance [5, 25, 96, 97], but is also associated with enhanced endurance performance [155–158]. Further research has examined the relationships between an athlete's strength and their performance in a variety of sports (Table 6).

The examined studies in Table 6 indicate that stronger athletes outperform their weaker counterparts with regard to both strength-power- and endurance-based sports or events. Collectively, 107 correlation magnitudes were reported with 101 (94 %) displaying a relationship with strength that was moderate or greater and 89 (83 %) displaying a large or greater relationship with strength. In support of these findings, several studies have examined sport performance differences between stronger and weaker subjects. These studies indicated that stronger cyclists had a faster 25-m track cycling time compared to weaker cyclists [37], stronger handball players had a greater standing and 3-step running throwing velocity compared to weaker handball players [93], and that stronger sprinters had a faster 100-m time compared to weaker sprinters [131]. The combined evidence of the comparisons between stronger and weaker athletes provides substantial support that stronger athletes within a relatively homogenous level of skill perform better in comparison to weaker athletes.

6 Influence of Strength on Additional Abilities

In addition to influencing an athlete's force-time characteristics, general sport skills, and specific sport skills, muscular strength may also influence several other training and performance characteristics. Some of the training and performance characteristics that may be influenced by muscular strength are the ability to potentiate when using strength-power potentiation complexes, the magnitude of potentiation that an athlete may achieve, and the reduction of injury risk.

6.1 Potentiation

Much research has investigated the acute effects of strength-power potentiation complexes on an individual's explosive performance. While a number of factors may influence one's ability to realize potentiation [167–169], one factor that may be modified through regular strength training is the individual's strength. In fact, previous

Table 6 Summary of studies correlating maximal strength and specific sport skill performance

Study	Subjects (n)	Strength measure	Performance measure	Correlation results
Beckham et al. [30]	Male and female intermediate to advanced weightlifters ($n = 12$)	IMTP, IMTPa	Snatch, C&J, total	IMTP: $r = 0.83$ (Snatch), $r = 0.84$ (C&J), $r = 0.84$ (Total) IMTPa: $r = 0.62$ (Snatch), $r = 0.60$ (C&J), $r = 0.61$ (Total)
Behm et al. [159]	Secondary school and current/former junior level hockey players ($n = 30$)	Dominant leg 1RM leg press dominant leg Rel 1RM leg press	On-ice skating time	$r = -0.30$ (1RM leg press), $r = -0.31$ (Rel 1RM leg press)
Carlock et al. [44]	National-level male and female junior and senior weightlifters ($n = 64$)	1RM BS, Rel 1RM BS	Snatch, C&J, Rel snatch, Rel C&J	1RM BS & Snatch: $r = 0.93$ (Men), $r = 0.79$ (Women), $r = 0.94$ (All) 1RM BS & C&J: $r = 0.95$ (Men), $r = 0.86$ (Women), $r = 0.95$ (All) 1RM BS: $r = 0.94$ (Snatch), $r = 0.95$ (C&J), $r = 0.38$ (Rel Snatch), $r = 0.36$ (Rel C&J) Rel 1RM BS: $r = 0.46$ (Snatch), $r = 0.50$ (C&J), $r = 0.80$ (Rel Snatch), $r = 0.85$ (Rel C&J)
Dumke et al. [160]	Well-trained male runners ($n = 12$)	IS (140° knee angle)	VO_2 at stages 1–6	$r = 0.57$ (Stage 4), No other data reported
Judge et al. 2011 [161]	Elite and NCAA division I male and female track and field throwers ($n = 57$)	1RM BS	Weight throw personal best	$r = 0.64$ (Males), $r = 0.80$ (Females)
Judge and Bellar [162]	Male and female track and field throwers coached by USA Track and Field level III certified coach ($n = 53$)	1RM BS, 1RM PC, 1RM BP	Shot put season best	$r = 0.77$ (1RM BS), $r = 0.87$ (1RM PC), $r = 0.77$ (1RM BP)
Loturco et al. [105]	Male and female Brazilian national team boxers ($n = 15$)	IHS	Punch impact	$r = 0.68$ (Fixed jab), $r = 0.83$ (Fixed cross), $r = 0.69$ (Self-selected jab), $r = 0.73$ (Self-selected cross)
Reyes et al. [163]	NCAA division III baseball players ($n = 19$)	3RM BP	Bat speed	$r = 0.51$
Speranza et al. [86]	Male first grade ($n = 10$), second grade ($n = 12$), and under 20 s ($n = 14$) semi-professional rugby league players	3RM BS, Rel 3RM BS, 3RM BP, Rel 3RM BP	Rugby tackle ability	3RM BS: $r = 0.67$ (All), $r = 0.72$ (First grade), $r = 0.55$ (Second grade), $r = 0.77$ (Under 20 s) Rel 3RM BS: $r = 0.41$ (All), $r = 0.86$ (First grade), $r = 0.60$ (Second grade), $r = 0.38$ (Under 20 s) 3RM BP: $r = 0.58$ (All), $r = 0.72$ (First grade), $r = 0.18$ (Second grade), $r = 0.70$ (Under 20 s) Rel 3RM BP: $r = 0.23$ (All), $r = 0.27$ (First grade), $r = 0.26$ (Second grade), $r = 0.08$ (Under 20 s)

Table 6 continued

Study	Subjects (n)	Strength measure	Performance measure	Correlation results
Speranza et al. [164]	Male semi-professional rugby league players ($n = 16$)	1RM BS	Rugby tackle performance	$r = 0.71$ (Tackling ability), $r = 0.63$ (Dominant tackles)
Stone et al. [165]	Male and female NCAA division I throwers ($n = 11$)	IMTP	Shot put, weight throw	Shot put: $r = 0.67$ (Pre), $r = 0.71$ (Mid), $r = 0.75$ (Post) Weight throw: $r = 0.70$ (Pre), $r = 0.76$ (Mid), $r = 0.79$ (Post)
Stone et al. [37]	National-level male and female cyclists ($n = 20$)	IMTP, Rel IMTP, IMTPa	Low gear (25 m, curve 1, back stretch, curve 2, finish split times), high gear (25 m, curve 1, back stretch, curve 2, finish split times)	IMTP & Low gear splits: $r = -0.49$ (25 m), $r = -0.54$ (Curve 1), $r = -0.52$ (Back stretch), $r = -0.50$ (Curve 2), $r = -0.50$ (Finish) Rel IMTP & Low gear splits: $r = -0.45$ (25 m), $r = -0.50$ (Curve 1), $r = -0.53$ (Back stretch), $r = -0.54$ (Curve 2), $r = -0.53$ (Finish) IMTPa & Low gear splits: $r = -0.45$ (25 m), $r = -0.50$ (Curve 1), $r = -0.51$ (Back stretch), $r = -0.52$ (Curve 2), $r = -0.51$ (Finish) IMTP & High gear splits: $r = -0.50$ (25 m), $r = -0.51$ (Curve 1), $r = -0.54$ (Back stretch), $r = -0.55$ (Curve 2), $r = -0.54$ (Finish) Rel IMTP & High gear splits: $r = -0.58$ (25 m), $r = -0.60$ (Curve 1), $r = -0.61$ (Back stretch), $r = -0.60$ (Curve 2), $r = -0.58$ (Finish) IMTPa & High gear splits: $r = -0.54$ (25 m), $r = -0.56$ (Curve 1), $r = -0.58$ (Back stretch), $r = -0.57$ (Curve 2), $r = -0.55$ (Finish)
Stone et al. [166]	Male and female national and international level weightlifters ($n = 65$)	1RM BS Rel 1RM BS	Snatch, clean, Rel snatch, Rel clean	1RM BS & Snatch : $r = 0.94$ (All), $r = 0.94$ (Men), $r = 0.79$ (Women) 1RM BS & Clean: $r = 0.95$ (All), $r = 0.95$ (Men), $r = 0.86$ (Women) Rel 1RM BS & Rel Snatch: $r = 0.80$ (All), $r = 0.68$ (Men), $r = 0.71$ (Women) Rel 1RM BS & Rel Clean: $r = 0.85$ (All), $r = 0.73$ (Men), $r = 0.81$ (Women)
Stone et al. [166]	Male and female elite-level American weightlifters ($n = 16$)	IMTP, Rel IMTP, IMTPa	Snatch, C&J, Rel snatch, Rel C&J, SnatchA, C&Ja	IMTP: $r = 0.83$ (Snatch), $r = 0.84$ (C&J) Rel IMTP: $r = 0.37$ (Rel Snatch), $r = 0.24$ (Rel C&J) IMTPa: $r = 0.50$ (SnatchA), $r = 0.50$ (C&Ja)

1RM one repetition maximum, *3RM* three repetition maximum, *BP* bench press, *BS* back squat, *C&J* clean and jerk, *C&Ja* allometrically-scaled clean and jerk, *IMTP* isometric mid-thigh clean pull, *IMTPa* allometrically-scaled isometric mid-thigh clean pull, *IS* isometric squat, *IHS* isometric half-squat, *PC* power clean, *Rel* relative, per kilogram of body mass, *SnatchA* allometrically-scaled snatch research indicated that greater magnitudes of potentiation can be achieved following strength training [170]. This may be attributed to the ability of stronger subjects to develop fatigue resistance to high loads as an adaptation to repeated high load training [171–174]. Additional research examined the relationships between the absolute and relative strength characteristics of subjects and the changes in performance following a potentiation protocol (Table 7).

Collectively, the studies displayed in Table 7 reported 67 Pearson correlation coefficients. Of those reported, 39 (58 %) displayed a moderate or greater relationship with strength, while 33 (49 %) displayed a correlation magnitude that was large or greater. In support of these findings, a number of studies have indicated that stronger subjects potentiate earlier [172, 185, 187] and to a greater extent [172, 178, 184–187, 192–195] compared to their weaker counterparts. However, other studies noted no statistical differences in the potentiation displayed between strong and weak subjects [196–198]. A possible explanation for the results of the latter studies may be the design of the examined strength-power potentiation complexes. Two of the studies [196, 197] did not report any statistical increases in vertical jump performance following the examined potentiation protocols, making comparisons between stronger and weaker subjects challenging. The remaining study [198] did not find any statistical differences within the stronger and weaker groups following the implemented potentiation protocols compared to the performances following the control protocol used. While relative strength is a major contributing factor to the timing and magnitude of potentiation, the design of the strength-power potentiation complex cannot be overlooked as it ultimately produces a state of preparedness for subsequent activity [168]. A second explanation for the lack of statistical differences between stronger and weaker subjects may be the range of the subjects' abilities within each group. For example, males and females were grouped together in one study when comparing potentiation differences between stronger and weaker subjects [197], while large standard deviations within groups may have prevented statistical differences from being found in another study [196].

Collectively, the previous literature indicates that by achieving greater strength, an individual may be able to realize potentiation effects at an earlier rest interval and to a greater extent. From a practical standpoint, some authors have noted that those with the ability to back squat at least twice their body mass to either parallel depth [184, 185, 187] or to 90° of knee flexion [199] may have a greater potential to potentiate their performance as compared to their weaker counterparts. Similarly, Berning et al. [193] indicated that a level of strength required to achieve greater magnitudes of potentiation is the ability to back squat at least 1.7 times one's body mass to parallel depth.

6.2 Injury Rate

Previous research has indicated that muscular strength may be as important as anaerobic power for performance as well as injury prevention in soccer players [200]. Along with winning, the rate of injuries in sports and training is one of the primary concerns of athletes, coaches, and practitioners. If athletes are injured in some capacity, they cannot contribute to the overall performance of the team on the field or court. From a coaching perspective, the introduction of new training modalities may not be well received because certain exercises are viewed as injurious. However, an appropriate and progressive prescription, using a variety of methods that focus on improving strength, may decrease the overall occurrence of injuries. Previous research has indicated that there was a decrease in the injury rate per 1,000 exposure hours in collegiate soccer players following the addition of a strength training program [201]. In addition, Sole et al. [202] indicated that the greatest value of team isometric mid-thigh pull strength coincided with the lowest annual injury rate experienced in female volleyball players. This evidence lends support to the idea that increases in strength may play an important role in reducing the occurrence of injuries. Several other studies [200, 203, 204] and reviews [205–208] support this concept. In fact, a meta-analysis indicated that the examined strength training protocols reduced sports injuries to less than one-third and that overuse injuries could be almost halved [207]. Resistance training may reduce the number of injuries due to increases in the structural strength of ligaments, tendons, tendon to bone and ligament to bone junctions, joint cartilage, and connective tissue sheaths within muscles [205]. Moreover, positive changes in bone mineral content as a result of resistance training may aid in the reduction of skeletal injuries. Collectively, the previous literature indicates that resistance training is a modality that may decrease injury rates and that stronger athletes are less likely to get injured. Therefore, a primary focus of strength and conditioning practitioners may be to increase the overall strength of their athletes in order to not only increase performance, but to also decrease the likelihood of an injury occurring.

7 Testing and Monitoring Strength Characteristics

Regular testing and monitoring of an athlete's performance may be the most effective way to provide useful information to the sport or event coaches about the athlete's training state [209, 210]. Moreover, this information can be used to prescribe and adapt training programs to provide an optimal training stimulus for athletes. With regard to

Table 7 Summary of studies correlating maximal strength and potentiation effects

Study	Subjects (n)	Strength measure	Potentiation test	Correlation results
Bellar et al. [175]	NCAA division I male and female track and field throwers ($n = 17$)	1RM PC	Weight throw distance	$r = 0.54$ (1RM PC), $r = 0.22$ (1RM BS)—Overweight 1
		1RM BS		$r = 0.55$ (1RM PC), $r = 0.23$ (1RM BS)—Overweight 2
Bevan et al. [176]	Professional rugby players ($n = 26$)	3RM BP	BP throw	$r = 0.52$ (8 min)
Chaouachi et al. [177]	Elite male volleyball players ($n = 12$)	1RM HS	CMJ height, PP, PF, PV, PPave	$r = -0.02$–0.12 (Time to max JH, PP, PF, PV, PPave)
				$r = -0.07$–0.12 (Potentiation response of JH, PP, PF, PV, PPave)
Duthie et al. [178]	Female hockey and softball players ($n = 11$)	1RM HS	Jump squat PP, PF	$r = 0.66$ (PP), $r = 0.76$ (PF)
Jo et al. [172]	Recreationally-trained men ($n = 12$)	Rel 1RM BS	Wingate time to PPmax	$r = -0.77$
Judge et al. [179]	NCAA division I male and female track and field throwers ($n = 41$)	1RM PC 1RM BS 1RM BP	Overhead back shot put throw	$r = 0.34$ (1RM PC), $r = 0.30$ (1RM BS), $r = 0.27$ (1RM BP)—heavy condition $r < 0.16$ (1RM PC, BS, BP)—light condition $r < 0.16$ (1RM PC, BS, BP)—control condition
Kilduff et al. [180]	Professional rugby players ($n = 23$)	3RM BS	CMJ PP	3RM BS: $r = 0.56$ (8 min), 0.63 (12 min)
		Rel 3RM BS		Rel 3RM BS: $r = 0.63$ (12 min)
Kilduff et al. [180]	Professional rugby players ($n = 23$)	3RM BP	BP throw PP	3RM BP: $r = 0.59$ (12 min)
		Rel 3RM BP		Rel 3RM BP: $r = 0.21$ (12 min)
Kilduff et al. [181]	Professional rugby players ($n = 20$)	3RM BS	CMJ height	$r = 0.49$ (8 min)
Mangus et al. [182]	Male weightlifters ($n = 11$)	Rel HS Rel QS	CMJ height	$r = -0.14$ (Rel HS), $r = -0.17$ (Rel QS)
Okuno et al. [183]	Male handball players ($n = 12$)	1RM HS	RSAbest, RSAave, RSAindex	$r = 0.03$ (RSAbest), $r = 0.50$ (RSAave), $r = 0.56$ (RSAindex)
Ruben et al. [184]	Resistance-trained men ($n = 12$)	1RM BS	Horizontal plyometric hurdle hops	$r = 0.82$ (PPave), $r = 0.53$ (PFave), $r = 0.70$ (PVave), $r = 0.81$ (PPmax), $r = 0.30$ (PFmax), $r = 0.77$ (PVmax)
Seitz et al. [185]	Male junior rugby league players ($n = 18$)	Rel 1RM BS	CMJ PP, time to PPmax, JH, time to JHmax	$r = 0.78$ (PP), $r = -0.69$ (Time to PPmax)
				$r = 0.74$ (JH), $r = -0.69$ (Time to JHmax)
Seitz et al. [132]	Male junior rugby league players ($n = 13$)	Rel 1RM BS Rel 1RM PC	20 m sprint potentiation response	$r = 0.56$ (Rel 1RM BS), $r = 0.63$ (Rel 1RM PC)
Suchomel et al. [186]	Resistance-trained men ($n = 15$)	Rel 1RM BS	SJ height potentiation response	Rel 1RM BS: $r = 0.52$ (Ballistic), $r = 0.63$ (Non-ballistic)
		Rel 1RM COHS		Rel 1RM COHS: $r = 0.57$ (Ballistic), $r = 0.48$ (Non-ballistic)
Suchomel et al. [187]	Resistance-trained men ($n = 16$)	Rel 1RM BS	SJ height maximum potentiation response	Rel 1RM BS: $r = 0.64$ (Ballistic), $r = 0.54$ (Non-ballistic)
		Rel 1RM COHS		Rel 1RM COHS: $r = 0.74$ (Ballistic), $r = 0.47$ (Non-ballistic)
Terzis et al. [188]	Male and female physical education students ($n = 16$)	6RM leg press	Underhand shot throw	$r = 0.50$

Table 7 continued

Study	Subjects (n)	Strength measure	Potentiation test	Correlation results
Tsolakis et al. [189]	Male and female international level fencers ($n = 23$)	1RM leg press	CMJ PP	$r = -0.55$ (12 min)
West et al. [190]	Professional rugby players ($n = 20$)	1RM BP	BP throw PP	$r = 0.63$ (Ballistic), $r = 0.68$ (Heavy resistance training)
Witmer et al. [191]	Male and female collegiate athletes and recreationally-trained athletes ($n = 24$)	1RM BS	CMJ height, vertical stiffness	CMJ height: $r = -0.54$ (Men), 0.10 (Women) CMJ vertical stiffness: $r = -0.43$ (Men), −0.36 (Women)
Young et al. [192]	Recreationally-trained men ($n = 10$)	5RM HS	Loaded CMJ height	$r = 0.73$

RM repetition maximum, *BP* bench press, *BS* back squat, *CMJ* countermovement jump, *COHS* concentric-only half-squat, *HS* half-squat, *IS* isometric squat, *PC* power clean, *PF* peak force, *PP* peak power, *PV* peak velocity, *QS* quarter-squat, *Rel* relative, per kilogram of body mass, *RSA* repeated sprint ability, *SJ* squat jump

testing and monitoring an athlete's strength, sport scientists and practitioners may use various tests to examine an athlete's isometric, dynamic, and reactive strength characteristics. The subsequent paragraphs briefly discuss previous research that has used isometric, dynamic, and reactive strength testing to examine the strength characteristics of individuals. For a thorough review on different methodologies of strength assessment, readers are directed to McMaster and colleagues [211].

Regular monitoring can also assist in better understanding the aforementioned relationships between maximal strength and performances, as the required motor learning strategies to manifest improvements in overall strength into skilled performance must be recognized. The delay between increased physical capacity and ability to actualize increased strength into improved performance is termed lag time [48, 212]. The concept of lag time, or the length of time it takes for an athlete to "learn to utilize their new found strength," is important to consider when trying to determine the transfer of training effect from one underlying physical attribute to an athletic skill such as sprinting and jumping. Thus, regular testing and assessment of the data is critical in order to assess or determine the lag within various activities.

7.1 Isometric Strength

As displayed in the tables above, many studies have assessed the maximum strength of subjects by using an isometric strength test such as the isometric mid-thigh pull, isometric squat, or isometric half-squat. While these tests do not provide a maximum load lifted, previous research has displayed notable relationships between the isometric strength tests and dynamic strength performance [29, 36, 106]. In addition to examining relationships between maximal isometric strength and various performance characteristics (Tables 1, 2, 3, 4, 5, 6, 7), isometric strength tests have been used to examine different phases of an exercise [213], the effect of a training program on muscular strength characteristics [29, 214], and determine force production differences among athletic teams [215]. The versatility of an isometric strength test should not be overlooked. Isometric strength tests are time efficient, particularly with large groups, and may provide a truer measure of "maximum" strength compared to dynamic strength testing in which the final load attempted may be overestimated. However, as with any maximal strength test, isometric strength tests should be used sparingly as they can be taxing for the individual and may require the need to slightly modify training during the day of testing.

Sport scientists and practitioners must keep in mind the sport specificity of the athlete when using isometric testing. In other words, the athlete must be tested in a position that is related to the success of their sport. For example, previous research has indicated that the greatest amount of force and power is produced during the second pull of weightlifting movements [216]. Thus, it would be logical to test weightlifters in a position that is specific to the second pull, as demonstrated by previous research [30, 166, 217]. Another example may be testing sprinters or bobsledders at hip and knee angles that correspond to different phases of speed development (i.e., acceleration, transition, velocity, competition speed) [218]. By testing the individual during each phase, the sport scientist and coach will receive information about the strengths and weaknesses of an athlete's overall sprinting performance. From here, modifications to the individual's training program can be made to eliminate any potential weaknesses. However, sport scientists and practitioners should keep in mind that performing such tests should not hinder athletes from completing their planned training program.

7.2 Dynamic Strength

While isometric strength testing has its advantages, so too does dynamic strength testing. Dynamic strength testing may be the most common method of measuring an individual's strength. This is typically accomplished by having the individual perform a repetition maximum (RM) test, where the individual lifts as much weight as possible for a specific number of repetitions. Examples listed in the Tables 1, 2, 3, 4, 5, 6, 7 include RM tests ranging from 1RM–6RM tests of either the back squat, front squat, half-squat, power clean, hang clean, leg press, or bench press. While the previous exercises have both eccentric and concentric muscle actions, additional studies have used concentric-only movements [186, 187, 219] or eccentric-only movements [150] to assess maximal strength characteristics within each of the muscle actions individually that comprise overall dynamic strength.

Dynamic strength tests may be viewed as more relevant to an athlete's abilities due to their similarities to movements completed in various sports or events. Previous research has used dynamic strength tests to examine the effect of specific training programs [124, 220], the effect that a competitive season had on muscular strength [221–224], and contributing factors that affect COD performance [150]. Similar to isometric strength testing, dynamic strength testing should be completed sparingly due to its taxing nature. While some practitioners use dynamic strength 1RM tests to prescribe training loads, others may discourage the practice of "maxing out." An alternative option for the latter practitioners would be to estimate an individual's 1RM using the set-rep best method described by Stone and O'Bryant [225]. The set-rep best method uses loads performed in training for a specific repetition scheme and estimates training loads for other repetitions schemes, but also a 1RM. This approach may be applied to any exercise, but may be the most useful for exercises that do not have specific criteria for a successful 1RM attempt, such as weightlifting pulling derivatives [226–236].

7.3 Reactive Strength

Reactive strength can be described as the ability of an athlete to change quickly from an eccentric to concentric muscular contraction [237]. The two primary methods of assessing reactive strength are through performing either drop jumps or countermovement jumps to calculate the variables reactive strength index (RSI; drop jump height × ground contact time^{-1}) or reactive strength index-modified (RSImod; countermovement jump height × time to takeoff^{-1}), respectively. Although different from maximal isometric and dynamic strength testing, previous research has indicated that there are strong relationships between maximal isometric strength and RSImod [238]. In addition, reactive strength testing can provide further information to the practitioners regarding how an individual achieves a certain standard of dynamic performance. For example, previous research examining RSI has determined that it is a reliable performance variable [239], can differentiate between field athletes with higher or lower acceleration abilities [129], can be used to monitor neuromuscular fatigue [240], and can be used as an indicator of the current training conditions [241]. Additional research has determined that RSImod is a reliable performance variable that can be used to monitor explosive performance acutely [242, 243], but also over the course of a competitive season [244]. Furthermore, RSImod can distinguish performance differences between teams [245], within teams [246], and can be used to assess an athlete's ability to effectively use the stretch-shortening cycle to achieve a specific jump height [247]. While scientific equipment is needed to assess RSI and RSImod [247], more information can be gathered that will provide practitioners with greater understanding of an individual's current performance capacity.

8 Absolute and Relative Standards of Strength

While absolute strength may be the deciding factor of which athlete is victorious in some sports (e.g. linemen in American football), the relative strength of an individual may be more important in certain sports where one must move their own body mass (e.g., track and field sprinting and jumping) or is competing in a sport that has weight class divisions (e.g., weightlifting). At present, no scales exist that recommend certain standards of relative strength

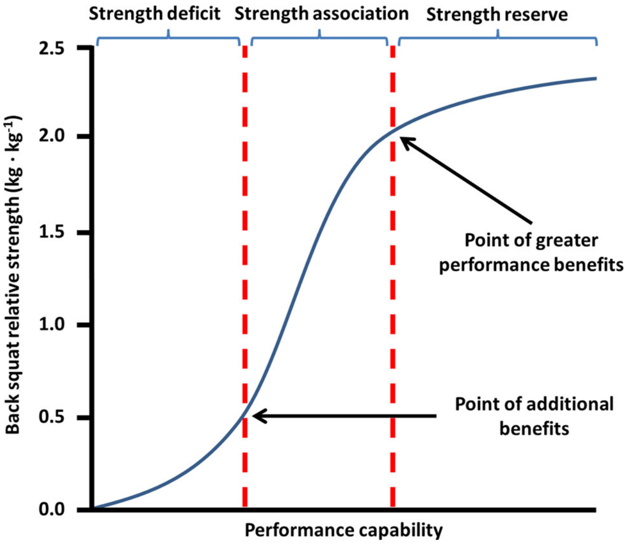

Fig. 1 Theoretical relationship between back squat relative strength and performance capability

for individuals in different sports; however, general recommendations can be made based on existing literature. Previous research has suggested that individuals who back squatted at least twice their body mass produced greater external mechanical power during a vertical jump [5, 12], sprinted faster and jumped higher [50], and potentiated earlier [185, 187] and to a greater extent [184, 185, 187] compared to individuals who did not. Figure 1 illustrates the theoretical relationship between relative back squat strength (per kilogram of body mass) and performance capabilities. It should be noted that this model is specific to the back squat based on the findings of the research presented earlier in this paragraph and the regular use of the back squat as a standard measure of strength. Moreover, the theoretical nature of the presented model should be emphasized. While a number of studies indicate that the ability to back squat at least twice one's body mass is indicative of a greater performance, information regarding specific standards of required strength is still lacking. The presented model indicates that there are three primary strength phases including strength deficit, strength association, and strength reserve. Previous work by Keiner et al. [248] provides a timeline for the presented model by suggesting that with 4–5 years of structured strength training, relative strength levels with the back squat should be at a minimum 2.0 for late adolescents (16–19 years old), 1.5 for adolescents (13–15 years old), and 0.7 for children (11–12 years old) (Fig. 2).

8.1 Strength Deficit Phase

The strength deficit phase may be the shortest phase based on the motor learning capacity of the individual. This phase suggests that although an individual is improving their

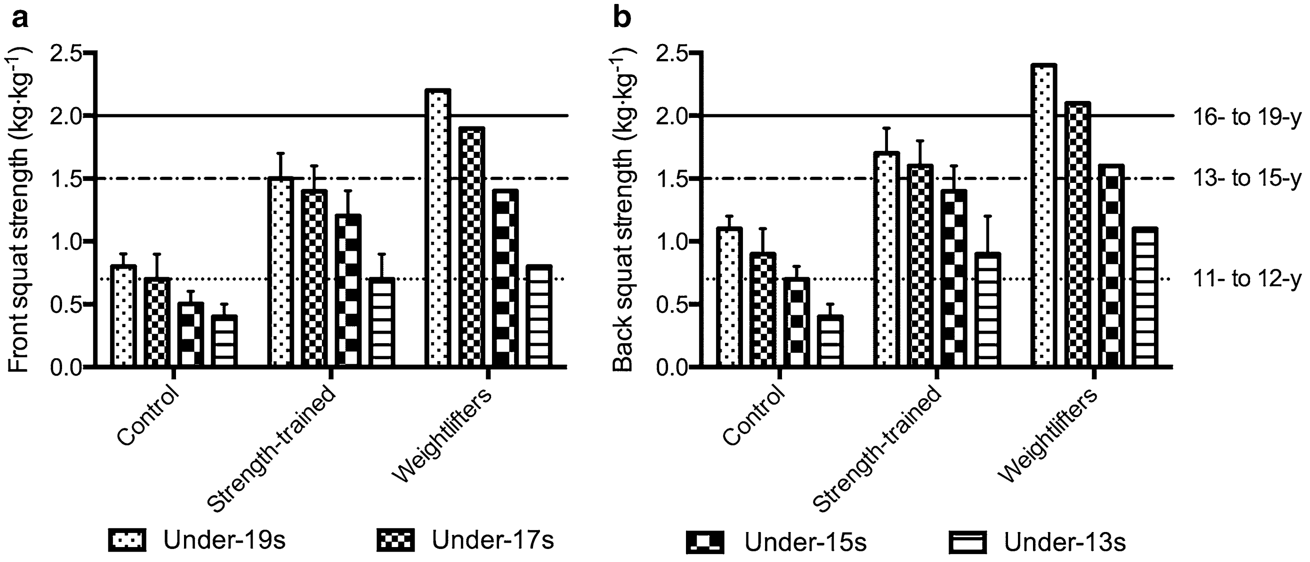

Fig. 2 Relative front squat (**a**) and back squat strength (**b**) comparison between control subjects (2 years of soccer training only; mean and standard deviation [SD]), strength-trained subjects (2 years soccer and strength training; mean and SD), and young elite weightlifters (mean only). Values for the weightlifters represent predicted one-repetition maximum (1RM) of the front squat and back squat based on their 5RM strength testing of the weight classes closest to that of the soccer players in each age group [281]. *Notes*: Weightlifters were tested with full depth squats and all soccer players (control- and strength-trained) were tested with parallel depth squats. *Lines* are drawn at the recommended standards of strength for young elite athletes with long-term training (a training age commensurate with appropriate resistance training from 7 or 8 years of age). Figure created by the authors from data in Keiner et al. [248]

strength (i.e., their ability to generate force), they may not be able to exploit their levels of strength and translate them into positive performance benefits in their respective sport. This is supported by the phasic progression concepts from previous literature [25, 63, 64] that indicates that central and local factors (i.e., motor unit recruitment, fiber type, and co-contraction) enhance the ability to increase maximum strength. Novice athletes within this phase are often going through stages of physical literacy, especially if they have not been previously exposed to strength training [249, 250]. The strength deficit phase will ultimately continue until the individual becomes competent with the strength training exercise.

8.2 Strength Association Phase

As the athlete gets stronger, he or she enters the strength association phase where increases in strength often directly translate to an improved performance. As indicated in the model, this phase is characterized by a nearly linear relationship between relative strength and performance capability. Specifically, further increases in maximum strength combined with central factors, the specificity of the task, and the coordination of multiple joints enhance an individual's ability to increase muscular performance [25, 63, 64]. The duration of this phase may be based primarily on two physiological mechanisms including muscle cross-sectional area or architectural changes and supraspinal/spinal neuromuscular adaptations that occur as a result of regular strength training. Specifically, the cross-sectional area or architectural changes that are characteristic of strength training are greater Type II/I functional cross-sectional area [251–253] and pennation angle changes [254–256]. The supraspinal/spinal neuromuscular adaptations include increases in motor unit rate coding [28, 257], neural drive [71, 258–260], inter- and possibly intra-muscular coordination [261–267], motor unit synchronization [268, 269], and the ability to use the stretch-shortening cycle, while decreasing neural inhibitory processes [63, 270]. Previous studies that have examined training for maximal strength have reported changes in muscle architecture after 4–5 weeks [271, 272] and increased tendon stiffness after 9–10 weeks [273, 274]. As changes in muscle architecture [20, 254] and tendon stiffness [275, 276] may affect the electromechanical delay and rate of force development during stretch-shortening cycle tasks, it is important to note the time needed for positive training adaptations to occur.

8.3 Strength Reserve Phase

The final phase of the proposed model is the strength reserve phase. Athletes who reach this phase have dramatically improved their ability to produce force primarily due to local and central adaptations and alterations in task specificity [25, 277, 278]. During the strength reserve phase, athletes may continue to gain relative strength; however, the direct benefits to performance may not be as substantial. In fact, a previous review indicated that while strength is a basic quality that influences an athlete's performance, the degree of this influence may diminish when athletes maintain a very high level of strength [279]. Thus, the window of adaptation for further strength enhancement is reduced as an individual increases their maximal strength. This may be why other literature has suggested that the emphasis of training may be shifted towards "power" or RFD training after a specific standard of strength has been achieved [25, 68, 279, 280]. That is not to say that individuals should not seek to continue improving their strength, rather stronger individuals can focus more on maintaining their strength, while placing more emphasis on RFD and speed adaptations. It should be noted, however, that limited research has examined the differences in performance between individuals that can squat greater than or equal to 2.5× their body mass versus 2.0× and 1.5×. Moreover, no research has discussed the changes in performance after transitioning from a 2.0× to a 2.5× body mass squat.

9 Limitations

The current review was primarily descriptive to provide a comprehensive description with as much of the literature represented as possible. The benefit of such a comprehensive description results in the limitation that a full meta-analytical review could come to stronger conclusions. However, each area of the current review would require a separate meta-analysis and therefore would suffer from not being able to draw on the multi-factorial discussion presented in the current review. Furthermore, it should be noted that much of the interpretation of existing studies came from correlational analyses and the readers should consider that correlation does not necessarily indicate causation.

10 Conclusions

While certain underlying factors of an athlete's performance cannot be manipulated (e.g., genetics), sport scientists and practitioners can manipulate an athlete's absolute and relative strength with regular strength training. Greater muscular strength can enhance the force-time characteristics (e.g., RFD and external mechanical power) of an individual that can then translate to their athletic performance. Muscular strength is strongly correlated to superior jumping, sprinting, COD, and sport-specific performance. Additional benefits of stronger individuals include the ability to take advantage of postactivation potentiation and a decreased injury rate. Sport scientists and practitioners may monitor the isometric, dynamic, and reactive strength of individuals in order to provide optimal training stimuli to enhance specific strength characteristics that translate to performance. It is recommended that athletes should strive to become as strong as possible within the context of their sport or event. Regarding relative lower body strength, it appears that the ability to back squat at least twice one's body mass may lead to greater athletic performance compared to those who possess lower relative strength. The vast majority of the literature supports the notion that stronger athletes demonstrate superior RFD and external mechanical power, and subsequently jump higher, run faster, perform COD tasks faster, potentiate earlier and to a greater extent, and are less likely to get injured. Therefore, sport scientists and practitioners could conclude that there may be no substitute for greater muscular strength as it underpins a vast number of attributes that are related to improving an individual's performance across a wide range of both general and sport specific skills while simultaneously reducing their risk of injury when performing these skills.

Despite the information described in this review, a number of research questions regarding the influence of strength on an athlete's overall performance still exist. Information regarding specific standards of required strength is still lacking. While a number of studies indicate that the ability to back squat at least twice one's body mass is indicative of a greater performance, no research has established standards for greater performance using isometric strength measurements. Furthermore, no levels of relative upper body strength that display a superior performance compared to lower relative strength have been reported. While general conclusions can be made with regard to the influence of strength on an athlete's performance, more research is needed with female athletes with regard to how their relative strength levels relate to their performance. Additional research with female athletes would allow for more specific recommendations to be made. The studies discussed within this review focused on bilateral strength measures, primarily because it may not be practical to perform a 1RM test with a single limb. However, due to the unilateral nature of certain sports and events (e.g., sprint events, hockey, etc.), further research examining the transfer of bilateral strength to single leg force-time characteristics and the transfer of single-leg strength training to bilateral force-time characteristics, strength, and overall performance is needed. Finally, future research should examine the effect of longitudinal resistance training, particularly with respect to long-term athlete development over several years to gain a better understanding of the influence of strength on the development and performance of an athlete.

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