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The Relationship Between Strength, Power, and Sprint Acceleration in Division I Men's Soccer Players

Christopher Bellon
East Tennessee State University

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by

Christopher R. Bellon

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Brad H. DeWeese, EdD, Chair

Kimitake Sato, PhD

Kenneth P. Clark, PhD

Michael H. Stone, PhD

ABSTRACT

The Relationship Between Strength, Power, and Sprint Acceleration in Division I Men's Soccer Players

by

Christopher R. Bellon

The purposes of this dissertation were three-fold. The first was to identify the approximate distances characterizing early-, mid-, and late-acceleration in a population of Division I men's collegiate soccer players. The secondary purpose was to investigate the relationships between various strength-power variables and key sprint characteristics during early-, mid-, and late-acceleration in a population of Division I men's soccer players. The final purpose of this dissertation was to compare the spatiotemporal characteristics of "strong" versus "weak" and "more powerful" versus "less powerful" Division I men's soccer players during early-, mid-, and late- acceleration. The following are the major findings of this dissertation. The early-, mid-, and late-acceleration zones within this sport population coincide with distances of approximately 0-2.5, 2.5-6, and 6-12m, respectively. Peak power (PP) and rate of force development (RFD) at 90ms appear to be strongly related to shorter ground contact times in each of these zones, while PP and RFD at 200 and 250ms showed strong relationships with step frequency during mid-acceleration. Not surprisingly, athletes who were characterized as "strong" or demonstrated "higher power outputs" appeared to achieve greater sprint velocity by expressing higher step frequency, particularly during mid-acceleration, as well as abbreviated ground contact times across each sub-section of acceleration. These results support the importance of developing high levels of maximal strength, PP, and RFD to enhance sprint acceleration. Additionally, these findings may also be used to strategically integrate speed development and resistance training

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practices into the annual training plan. The amalgamation of these training variables may allow

practitioners to better manage fatigue and elicit desired performance adaptations at the

appropriate times of the training year.

DEDICATION

This dissertation is dedicated to my parents, Jeannie and Steven Bellon, for their unconditional love and support through all of life's challenges. Thank you for every 6AM skating session, every weeknight spent in an ice rink, and every weekend that you sacrificed to allow me to play the game I loved. Each lesson was another stepping stone preparing me for life after hockey, and the driving force in finishing this chapter of my life. I love you both and look forward to the endless possibilities the future may hold.

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CHAPTER 1

INTRODUCTION

The nature of competition in field sports is inherently chaotic. Often times, sports such as soccer, rugby, and field hockey showcase a fast-paced style of gameplay consisting of short-sprints and frequent changes of direction (Duthie, Pyne, Marsh, & Hooper, 2006; Gregson, Drust, Atkinson, & Salvo, 2010; Jovanovic, Sporis, Omrcen, & Fiorentini, 2011; Murphy, Lockie, & Coutts, 2003). Due to this intermittent style of competition, field sport athletes (FSA) rarely attain maximum sprint velocity during match-play (Cronin & Hansen, 2005; Murphy et al., 2003). Accordingly, the ability to accelerate is a coveted skill in this athlete population. Aside from the obvious benefits related to gameplay, sprint acceleration has also been shown to differentiate levels of playing ability in FSA, as higher-level players appear to cover short distances at a more rapid pace than their lower-level counterparts (Ferro, Villacieros, Floria, & Graupera, 2014; Gabbett, Kelly, Ralph, & Driscoll, 2009; Gabbett, Kelly, & Sheppard, 2008; Gissis et al., 2006). Based on this information, it should come as no surprise that enhancing this performance quality is often a primary focus in the development of these athletes.

While common tactics used to develop this skill include resistance training, resisted sprint training, plyometrics, and sprint drills (Cronin & Hansen, 2006; Delecluse, 1997; Martinez-Valencia et al., 2015), the way each of these tools are implemented varies from one practitioner to the next. Perhaps an even more glaring issue, however, is the lack of integration with other training components such as resistance training and sport practice. The evolution of an integrated approach is critical to the organization of the training process, as each facet of training represents a physiological stimulus applied to the athlete. As Stone, Stone, and Sands (2007) remind us, the adaptations underpinning improvements in sport performance are the result of

chronic training stimuli. Keeping this in mind, harmonizing these physiological stimuli likely plays a vital role in effectively managing fatigue and maximizing performance capabilities at the desired time of the training year.

An approach that addresses these concerns, referred to as Seamless Sequential Integration (SSI), has been proposed by DeWeese, Sams, and Serrano (2014a, 2014b). Specifically, SSI encompasses block periodization (BP), conjugate-sequential sequencing (CSS), and a short-to-long approach (S2L) to speed development (DeWeese et al., 2014a, 2014b). Generally, these methods aim to harmonize the physiological adaptations derived from resistance training, sport training, and speed enhancement, respectively. In particular, the S2L emphasizes the augmentation of acceleration early in the training year to bolster greater top-end speed during the competitive season (DeWeese, Sams, Williams, & Bellon, 2015). When combined with the tenants of BP and CSS, the acceleration and transition phases of sprinting are generally coupled with the development of strength endurance (SE) and maximal strength (MS), respectively, while maximum sprint velocity is often addressed while peak power outputs (PP) and high rates of force development (RFD) are being expressed (DeWeese, Bellon, Magrum, Taber, & Suchomel, 2016). Despite the utility of this approach, SSI was originally intended for track and field and bobsled athletes (DeWeese et al., 2014a, 2014b) who accelerate distances of approximately 35-60m (Mackala, Fostiak, & Kowalski, 2015) and 30-50m (DeWeese et al., 2014a) during competition, respectively. In contrast, FSA, such as soccer players, appear to spend the majority of their time covering shorter distances of approximately 9-15m (Bangsbo, Norregaard, & Thorso, 1991; Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001; Vigne, Gaudino, Rogowski, Alloatti, & Hautier, 2010).

Consequently, it may be more appropriate to adapt a S2L for this athlete population. This is not to say that greater sprint distances and velocities should be neglected. In fact, occasionally attaining maximum sprint velocity during training may offer neurological adaptations that are beneficial to acceleration (Ross, Leveritt, & Riek, 2001). With that said, however, it cannot be ignored that soccer players rely much more on short accelerations during competition. Additionally, there has also been an exponential rise in the number of competitions per training year in recent decades (Issurin, 2008), which has inherently diminished the time that can be dedicated towards training. Therefore, appropriately allocating training time to cultivate the most relevant skills to the sport is a logical approach in addressing this issue. From a speed development perspective, it may be wise to bolster sprint acceleration by addressing the constituent sub-phases, such as early-, mid-, and late-acceleration, rather than addressing the entire phase as a whole.

When combined with BP and CSS, a S2L for FSA would likely elicit similar physiological responses as those seen in the traditional model, which may facilitate comparable performance adaptations. For example, supplying "concentrated loads" of activities geared towards improving early-acceleration and SE during the general preparatory phase of training may allow the athlete to enhance both qualities without interfering with one another, as the higher resistance training volumes will likely be off-set with shorter sprint distances. From a physiological standpoint, this may limit the interference effect by maximizing the up-regulation of the mTOR pathway, while mitigating excessive phosphorylation of AMPk (Nader, 2006). Ultimately, these biochemical alterations may lead to greater levels of MS, RFD, and speed (Stone, Stone, & Sands, 2007). Despite the utility of this model, the foundation of this

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framework hinges on identifying appropriate distances constituting "early-", "mid-", and "late-acceleration".

While these sub-sections of sprint acceleration have been more clearly defined in the realm of track and field (Mackala et al., 2015; Mann, 2013; Nagahara, Matsubayashi, Matsuo, & Zushi, 2014), to the author's knowledge, only one study has investigated how this phase can be differentiated into early, mid, and late segments in FSA (Barr, Sheppard, & Newton, 2013). However, this study examined the acceleration profiles of elite rugby players, who likely possess different kinematics in comparison to soccer players. Furthermore, to foster a complete understanding of how to enhance sprint performance in each of these sub-phases, it may also be important to investigate the kinetic parameters governing each segment as well. Such information may assist in selecting appropriate speed development methods when aiming to improving early-, mid-, or late-acceleration. For instance, if the late-acceleration zone appears to most related to RFD, this may warrant the use of sled towing to potentiate this performance variable and, subsequently, acceleration performance at those particular distances (Winwood, Posthumus, Cronin, & Keogh, 2015). Lastly, the appropriateness of each method may differ based on the strength level of the athlete, as increasing muscular strength and power appears to alter the motor patterns employed during coordinated movement (Cormie, McGuigan, & Newton, 2010b). Therefore, it is feasible that stronger, more powerful athletes may display different spatiotemporal characteristics during acceleration in comparison to weaker, less powerful individuals resulting from the expression of greater force outputs. Ultimately, exploring these areas of study may provide the means to effectively develop an adapted version of SSI for FSA.

Dissertation Purposes

1. To identify the approximate distances characterizing early-, mid-, and late-acceleration in a population of Division I men's collegiate soccer players.

2. To investigate the relationships between various strength-power variables and key sprint characteristics during early-, mid-, and late-acceleration in a population of Division I men's soccer players.

3. To compare the spatiotemporal characteristics of "strong" versus "weak" and "more powerful" versus "less powerful" Division I men's soccer players during early-, mid-, and late- acceleration.

Operational Definitions

1. Allometric scaling – the process of scaling an absolute value in accordance with an athlete's body shape and size, which is mathematically expressed as the quotient of the variable in question and the athlete's body mass raised to the two thirds power.

2. Concentrated load – a unidirectional load emphasizing the development of a particular fitness characteristic.

3. Ground contact time – the time over which the foot is in contact with the ground during the stance phase of sprinting.

4. Impulse – the total force produced over a given timeframe.

5. Maximum sprint velocity – the highest rate at which an athlete can displace his or her body mass in a given direction.

6. Power – the rate at which mechanical work is performed, often calculated as the product of *force (F) x velocity (v)*.

7. Rate of force development – the frequency at which force is applied over a given timeframe.

8. Sprint – a maximal running effort over a given distance.

9. Sprint acceleration – the rate at which velocity increases during a sprint effort.

10. Sprint velocity – the rate at which an athlete is able to displace his or her body mass in a given direction.

11. Step frequency – the rate of steps taken over a period of one second.

12. Step length – the distance between consecutive foot contacts during a sprint effort.

13. Strength – the ability to produce force against an external resistance.

CHAPTER 2

COMPREHENSIVE REVIEW OF LITERATURE

The Importance of Sprint Speed and Acceleration in Sport

Sprint speed is perhaps the most coveted skill in the world of athletics. While sprint ability has obvious value in the world of track and field, it is also a critical component across a variety of team sports as well. Most notably, sprint speed has been shown to differentiate levels of playing ability in team sports such as American football (Black & Elmo, 1994; Fry & Kraemer, 1991), rugby (Gabbett, 2009; Gabbett et al., 2008), soccer (Bangsbo et al., 1991; Cometti et al., 2001; Eniseler, Camliyer, & Gode, 1996; Gissis et al., 2006; Reilly, Williams, Nevill, & Franks, 2000), baseball (Hoffman, Vazquez, Pichardo, & Tenenbaum, 2009), basketball (Hoare, 2000; Hoffman, Tenenbaum, Maresh, & Kraemer, 1996; Shalfawi, Sabbah, Kailani, Tonnessen, & Enoksen, 2011), and even ice-hockey (Farlinger, Kruisselbrink, & Fowles, 2007; Krause et al., 2012; Peyer, Pivarnik, Eisenmann, & Vorkapich, 2011). This differentiation elucidates the simple fact that while other sport skills such as shooting, hitting, or even throwing may be valuable, sprint speed ultimately dictates an athlete's opportunity to effectively utilize those abilities during competition.

This concept was clearly shown by Fry and Kraemer (1991) who investigated the sprint ability of Division I, II, and III collegiate football players in a 40-yard maximal running effort. The overall conclusion of the study was simple: Division I football players displayed faster sprint times in the 40-yard dash compared to Division II and III players. Furthermore, Division I athletes were also found to be faster than the Division II and III players when comparing the participants by position (i.e. – offensive backs, offensive line, receivers, defensive backs, defensive line, and linebackers). The only exception to this trend was with respect to the

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defensive backs. Also, with the exception of offensive lineman, the starters displayed faster sprint times than the non-starters. A similar result on the dichotomy between starters and support players was provided by Black and Elmo (1994). These investigators also found 40-yard sprint times to be a discriminating variable between starters and non-starters in NCAA Division 1-A college football players. While these findings may be very useful to practitioners working with football players, the trend is not exclusive to this sport population.

For instance, this concept was also echoed in multiple studies by Hoffman and colleagues in (1996) and (2009) regarding basketball and baseball, respectively. In 1996, the authors investigated the relationship between athletic performance tests and playing time in Division I male college basketball players across multiple seasons. The results of this study revealed that 27-meter sprint speed showed moderate-to-high correlations with playing time over a two-year time period. Similarly, Hoffman et al. (2009) compared 10-yard sprint speed over a 2-year period in major league (MLB) versus minor league (Rookie, A, AA, AAA) baseball players to investigate if this variable could positively distinguish MBL players from minor league athletes. The findings of this investigation indicated that MLB players were significantly faster than Rookie ball, A, and AA minor league players.

Interestingly, similar results were found by Gabbett et al. (2008) in rugby players. The purpose of their study was to identify if speed and agility field tests could differentiate between "higher-level" and "lower-level" skilled players based on their ranks within the same rugby club. The speed test implemented was a 20-meter sprint with 5-meter, 10-meter, and 20-meter split times. The findings revealed that the sprint times of "higher-level" players were statistically faster sprint times at every distance in comparison to "lower-level" players. An obvious limitation to this study, however, was that these players were all apart of the same rugby club. As

such, a further exploration was needed to identify if sprint ability is able to differentiate elite and sub-elite rugby athletes. This was exactly the purpose of a follow-up study by Gabbett et al., (2009), which aimed to highlight the physical qualities separating elite versus sub-elite junior rugby players. Similar to the previous investigation, the athletes performed a continuous sprint with splits at multiple distances. In this study, however, those splits were at distances of 10-meters, 20-meters, and 40-meters. The findings of this study indicated that, like higher and lower skill level players within the same organization, elite and sub-elite players can be effectively separated by sprint ability. Specifically, the differences in sprint times and velocities between the two groups were statistically significant, with the elite group displaying markedly superior sprint ability in comparison to their sub-elite counterparts. The magnitude of these differences was also supported by large to very large effect sizes at all sprint distances.

Up to this point, the studies presented have focused on sports that are predominantly anaerobic in nature (i.e. – football, basketball, baseball, rugby) (Bompa & Haff, 2009). While sprint speed is more relevant to power-oriented activities, sports that possess greater aerobic demands are also heavily influence by this skill as well. For example, this concept was clearly illustrated in multiple studies with respect to soccer players (Cometti et al., 2001; Eniseler et al., 1996; Ferro et al., 2014; Gissis et al., 2006). Additionally, these studies also highlight that fact that playing ability may be better discriminated by sprint acceleration rather than maximum sprint velocity. In the context of field sport athletes, sprint acceleration is often defined as "sprint performance over smaller distances, such as 5m or 10m" (Murphy, Lockie, & Coutts, 2003). Moreover, a number of these studies have indicated that sprint ability over such distances has shown to positively separate "national" and "first level" professional soccer players from their regional and lower-tier counterparts, respectively (Cometti et al., 2001; Ferro et al., 2014; Gissis

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et al., 2006). Specifically, a study by Commetti (2001) aimed to compare the sprint ability in elite, sub-elite, and amateur French soccer players over 10- and 30-meter distances. While the difference in 10-meter sprint speed between elite and amateur players was statistically significant, 30-meter sprint speed did not display this difference. Similar results were also found in a later study by Gissis et al. (2006) who examined sprint ability over 10-meters in elite, sub-elite, and amateur Greek soccer players. Like the previous study by Commetti (2001), the elite players displayed statistically greater sprint speeds over this distance when compared to the amateur players. This study, however, also found the differences in sprint speed between the elite and sub-elite groups to be statistically significant as well, something that was not found in the previous investigation. Lastly, a recent study by Ferro et al. (2014) compared sprint ability between "competitive" versus "recreational" soccer players over 30-meters with split times for the 0-10, 10-20, and 20-30 meter segments. Compared to the recreational participants, the competitive soccer players displayed statistically greater sprint velocities from 0-10 and 10-20 meters, but not during the 20-30 meter portion.

This trend is significant in the world of athletics, particularly in team sports, as competition often requires athletes to sprint across a variety of distances with frequent changes of direction occurring prior to reaching maximal velocity (Duthie et al., 2006; Jovanovic et al., 2011; Murphy et al., 2003; Young, McLean, & Ardagna, 1995). This concept is clearly illustrated in time-motion analysis data across a number of sports including soccer (Gregson et al., 2010), rugby (Cunniffe, Proctor, Baker, & Davies, 2009), field hockey (Gabbett, 2010), and basketball (Ben Abdelkrim et al., 2010), all of which display average sprint distances below 20-meters. This has been attributed to the fact that bursts of acceleration most often occur during key points in match play such as evading a defender or creating a scoring opportunity (Faude,

Koch, & Meyer, 2012; Meir, Colla, & Milligan, 2001; Rienzi, Drust, Reilly, Carter, & Martin, 2000). Based on this information it's not surprising that coaches often prioritize the development of acceleration with their athletes, as this skill can serve as a potent offensive or defensive weapon during competition.

The Development of Acceleration in Sport

Despite the wide range of methods used to enhance sprint acceleration, typical modalities most often include resistance-training, plyometrics, resisted sprinting, and sprint drills (Cronin, Hansen, 2006; Delecluse, 1997; Martinez-Valencia et al., 2015). The majority of these tools aim to improve acceleration through the training principle of specificity, which states that performance adaptations are specific to the demands imposed upon the individual (Stone, Stone, & Sands, 2007). Specifically, training methods such as plyometrics, resisted sprinting, and sprint drills aim to mimic the spatiotemporal characteristics of sprinting, in hopes of fostering a positive transfer of training effect. An argument can even be made that resistance training provides a level of "kinetic specificity", as the high ground reaction forces (GRF) inherent to sprinting may be similar to those achieved with certain resistance training practices (DeWeese, Bellon, Magrum, Taber, & Suchomel, 2016). Ultimately, sprinting is a complex skill that harmonizes a wide range of biomechanical and kinetic parameters. Due to the multifaceted nature of this skill, a single method or drill cannot stand alone as the primary tool for improving sprint performance. Rather, an integrated approach utilizing a combination of these methods is likely the most efficient way to develop speed (Cappadona, 2013; DeWeese, Sams, Williams, & Bellon, 2015; Rumpf, Lockie, Cronin, & Jalilvand, 2015; Young, 2006).

Resistance Training

        While many coaches perceive plyometrics, sprint drills, and resisted movement training to be the most effective methods of acceleration development, perhaps the most efficient tool is that of resistance training. In fact, there is a wealth of evidence displaying a clear relationship between maximal strength and sprint performance, particularly sprint acceleration (Baker, Nance, 1999; Barr, Sheppard, Agar-Newman, & Newton, 2014; Comfort, Bullock, & Pearson, 2012; Cunningham et al., 2013; Delecluse, 1997; Gissis et al., 2006; McBride et al., 2009; Seitz, Reyes, Tran, Saez de Villarreal, & Haff, 2014; Sleivert & Taingahue, 2004; Thomas, Comfort, Chiang, & Jones, 2015). Accordingly, whether coaches are aware of it or not, the principle of progressive overload is often utilized as a primary method of improving acceleration. A recent meta-analysis by Seitz and colleagues (2014) makes it abundantly clear that there is a positive transfer of lower-body strength training to sprint acceleration, as 50 of the 52 studies included in this investigation employed sprint tests at distances of less than 30-meters. The authors also noted that a primary conclusion of their analysis was that sprints over these short distances are highly dependent upon kinetic parameters such as "speed-strength" and "maximal power production". More specifically, strength-power variables commonly correlated to sprint acceleration include rate of force development (RFD) (Marques, Gil, Ramos, Costa, & Marinho, 2011; Marques & Izquierdo, 2014; Martinez-Valencia et al., 2015; Sha, 2014; Thomas et al., 2015), impulse (IP) (Hunter, Marshall, & McNair, 2005; Sha, 2014; Thomas et al., 2015), and power (P) (Baker & Nance, 1999; Cronin & Hansen, 2005; Lopez-Segovia, Marques, van den Tillaar, & Gonzalez-Badillo, 2011; Marques & Izquierdo, 2014). Keeping this in mind, the development of these critical qualities is essential to developing sprint acceleration.

It is important to note, however, that despite the strong relationship between power-related characteristics (i.e. – RFD, IP, PP) and sprint acceleration, the importance of an athlete's maximal strength capabilities cannot be understated. This concept is also commonly misunderstood; as many coaches argue the duration of common sport skills are too short for athletes to express maximal strength. This argument is often made in reference to the short ground contact times inherent to sprinting, as elite sprinters typically display ground contact times (GCT) as short as 140 and 87 milliseconds during acceleration and maximum velocity, respectively (Mann, 2013). While the brevity of these movements may limit an athlete's ability to express maximal strength, a critical concept to understand is that maximal strength is more than the ability to produce force. Rather, it is the means by which RFD, P, and IP are developed (Stone, Moir, Glaister, Sanders, 2002; Stone, Stone, & Sands, 2007). In other words, maximal strength is the vehicle that drives the development of these strength and power qualities, as stronger athletes have been shown to display greater RFD (Beckham et al., 2013; Haff et al., 1997; Hornsby, 2013; Sole, 2015; Stone, Stone, & Sands, 2007), P (Cormie, McGuigan, & Newton, 2010c; Stone, Moir, Glaister, Sanders, 2002; Stone, O'Bryant, et al., 2003; Stone, Sanborn, et al., 2003; Stone, Stone, & Sands, 2007), and IP (Cormie, McGuigan, & Newton, 2010a, 2010b; Cormie et al., 2010c; Hornsby, 2013). Therefore, strength and speed are not separate entities, but are rather interrelated. Simply put, in order to develop the power-related qualities that are most relevant to sprint acceleration, an athlete's maximal strength must be made a priority (Haff & Stone, 2015; Taber, Bellon, Abbott, & Bingham, 2016).

Plyometrics

Sprinting is a skill that occurs in multiple planes of movement and requires the effective use of the stretch-shortening cycle (SSC) (Harrison, Keane, & Coglan, 2004). Based on this

information, practitioners often utilize plyometrics to overload the SSC in movements that appear mechanically similar to sprinting. Additionally, it has also been suggested that exercises offering the most efficient transfer to sprinting are those that include muscle contraction velocities similar to the task involved (Rimmer & Sleivert, 2000). With respect to plyometrics, this most often includes sprint acceleration (Rimmer & Sleivert, 2000), as the GCT and contraction velocities in exercises such as bounding and depth jumps closely resemble this phase of sprinting (Walsh, Arampatzis, Schade, & Bruggemann, 2004; Young, 1992). Also, it has long been established that ballistic exercises performed with maximal intent likely recruit type II motor units (Desmedt & Godaux, 1977). As such, many advocate the use of plyometrics to activate the high threshold motor units (HTMU) inherent to sprint acceleration, which would theoretically enhance the performance of this skill. This notion is supported in a review by Markovic and Mikulic (2010), who show a longitudinal trend in the improvement of sprint acceleration within training programs that utilize plyometrics. An even more interesting point made by the authors was that the average performance improvements tend to decrease at further sprint distances, particularly after 20 meters. Therefore, the vast majority of data indicate that plyometric exercises may be more beneficial in improving sprint acceleration in comparison to maximal velocity.

This point is also true from the perspective of developing leg and tissue stiffness, as plyometric exercises can also be used to develop these qualities and possibly sprint acceleration (Foure, Nordez, & Cornu, 2010, 2012; Foure, Nordez, McNair, & Cornu, 2011; Lloyd, Oliver, Hughes, & Williams, 2012). These adaptations may be valuable with respect to speed development, as it has been suggested that greater musculotendinous unit (MTU) stiffness may be advantageous to facilitating greater RFD (Brughelli & Cronin, 2008). This adaptation may

pave the road to greater sprint velocities by means of increasing GRF over the brief contact times experienced during sprinting. However, the relative contribution of leg-stiffness also appears to be dependent upon the velocity at which the athlete is sprinting, as leg-stiffness has been more closely related to the transition and maximum velocity phases than acceleration (Bret, Rahmani, Dufour, Messonnier, & Lacour, 2002; Chelly & Denis, 2001). Conversely, faster athletes have also been shown to display slightly greater leg stiffness during acceleration in comparison to their slower counterparts (Lockie, Murphy, Knight, & Janse de Jonge, 2011). The findings of Kuitunen, Komi, and Kyrolainen (2002) may explain this discrepancy, as these investigators characterized the patterns of ankle and knee stiffness with increasing running speeds. The authors concluded that ankle stiffness remains fairly constant from the beginning of acceleration to maximum velocity, while the knee joint displays a constant increase from the beginning of acceleration to top speed. Accordingly, the rigidity of the knee joint appears to be the primary source of increased leg stiffness contributing to faster sprint velocities in later stages of the sprints. Considering that the early acceleration phase contains minimal knee flexion during ground support (Nagahara, Matsubayashi, et al., 2014), it makes sense that this joint is a primary contributor during both acceleration and maximum velocity.

Despite the secondary role of ankle rigidity in developing greater leg-stiffness, this quality may still be an important consideration in improving acceleration. Theoretically, if an athlete develops a greater level of ankle stiffness through training, they may become more efficient in their ability to utilize the stored elastic energy in the MTU, which may lead to enhanced function of the stretch-shortening cycle (SSC). This is significant to sprinting in that greater efficiency of the SSC likely translates to greater forces being expressed during ground contact (Komi, 2008). This point was made in a study by Cornu and Goubel (1997) who showed

that 7-weeks of plyometric training increased passive stiffness and decreased active stiffness of the ankle by 52% and 32%, respectively. The authors noted that the increase in passive stiffness may be beneficial to increasing RFD, possibly by limiting the deformation imposed by GRF, while decreased active stiffness may be more desirable for storing and utilizing the potential kinetic energy of the MTU. Keeping this in mind, plyometric training may assist in developing this quality, likely through increasing the functional capacity of the Achilles tendon and triceps surae musculature (Foure et al., 2010, 2012; Foure et al., 2011; Kuitunen et al., 2002). This is perhaps a result of positive changes in the intrinsic mechanical properties of the tissue, such as increased cross-linkages within the collagen matrix of the Achilles tendon and a fiber-type shift towards the type IIx phenotype in the triceps surae (Almeida-Silveira, Perot, Pousson, & Goubel, 1994; Foure et al., 2011).

Considering the evidence provided, plyometrics may be a worthwhile means of improving acceleration ability. It is important to note, however, that a number of studies suggest that this training modality is likely complimentary to other methods, such as resistance training (Ford et al., 1983; Perez-Gomez et al., 2008; Ronnestad, Kvamme, Sunde, & Raastad, 2008) and conventional sprint training (Rimmer & Sleivert, 2000), rather than a primary training tool. The reason for this is that many of the performance benefits derived from plyometrics can also be achieved through these other methods. For example, similar connective tissue adaptations as those previously mentioned can also achieved through resistance training (Folland & Williams, 2007; Stone, Stone, & Sands, 2007). In addition, other studies have found also conventional sprint training to yield similar or even superior results to improving sprint acceleration in comparison to plyometrics (Luebbers et al., 2003; Rimmer & Sleivert, 2000). While there is some evidence to support the implementation of plyometrics in concert with resistance training

(Dodd & Alvar, 2007; Perez-Gomez et al., 2008), another study found no change in sprint performance (Faigenbaum et al., 2007). Considering the inconsistency of these findings, plyometrics may serve as a valuable secondary tactic to resistance and sprint training, but should be used judiciously in the training process.

<u>Resisted Sprinting</u>

Another common method in improving sprint ability is resisted sprinting. Common means of resistance include but are not limited to pulling sleds, pushing sleds, elastic bands, weight vests, and even motor vehicles (Hoffman, 2014; Hrysomallis, 2012). Despite the array of implements used to provide resistance, each are intended to increase an athlete's ability to produce higher GRF without compromising proper sprint mechanics (Kawamori, Newton, & Nosaka, 2014). Although the use of resisted sprint training to improve maximum velocity has been largely unsupported, there is a wealth of research validating its usefulness in improving sprint acceleration (Hrysomallis, 2012; Kawamori, Newton, Hori, & Nosaka, 2014b; Lockie, Murphy, & Spinks, 2003; Spinks, Murphy, Spinks, & Lockie, 2007; Zafeiridis et al., 2005).

Despite the convincing research support for this method, the appropriate implementation of this type of training remains unknown. For example, in order to foster a positive transfer of training effect, determining the appropriate resistance during sprint training is paramount. Selecting a load that is too heavy may compromise the athlete's sprint mechanics and defeat the purpose of the exercise (Kawamori, Newton, Hori, & Nosaka, 2014a). If a load is too light, however, the athlete may not receive a sufficient stimulus to elicit the intended higher GRF during their training. Some coaches advocate standardizing the use of 10% of the athlete's bodyweight (Hrysomallis, 2012), while others prefer to choose a load that decreases sprint velocity by no more than 10% (Clark, Stearne, Walts, & Miller, 2010). Recent evidence even

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supports the notion of using heavier loads that reduce sprint velocity up to 30% to improve acceleration ability (Kawamori, Newton, et al., 2014b). Clearly, the optimal loading scheme to improve sprint acceleration is likely dependent on a variety of factors, which may include the athlete's sport, position, and strength levels. Other considerations regarding the proper implementation of resisted sprint training are the type of implements used (e.g. – sled pushing versus pulling), surface, and training volume and frequency. Taking these factors into consideration, it is likely that the best practices of resisted sprint training depend not only on the goals and capabilities of the athlete, but also on the focus of training at a particular time of the year.

Sprint Drills

Historically, many coaches believe that sprinting is best learned by teaching the body to feel and respond to external stimuli, or "kinesthesis" (McFarlane, 1993). Based on this foundational belief, practitioners often use sprint drills to develop and rehearse movement patterns that are inherent to sprint technique (McFarlane, 1993). For example, McFarlane (1993) has previously proposed the "basic technical model" for speed, which encompasses a number of sprint drills designed to address acceleration, transition, and maximum velocity mechanics. Although a vide variety of drills are used to meet these objectives, two drills that are most central to this model are "A-drills" and "B-drills". Originally proposed by Gerard Mach, these drills were designed to mimic acceleration and maximum velocity kinematics, respectively (Cappadona, 2013; Kivi & Alexander, 1997; McFarlane, 1993). However, how and when these movements are utilized may differ from one coach to the next. In a study by Kivi and Alexander (1997), the authors interviewed a number of high-level track and field coaches from the United States and Canada to inquire why, how, and when the Mach drills were implemented in their

athletes' training programs. The responses typically included rationales such as emphasizing

proper movement mechanics, improving neuromuscular strength and endurance, and enhancing

nerve conduction velocity. However, when asked to elaborate on how the drills were taught and

where they fit into the big picture of their methodology, it is obvious that these drills actually

utilized quite differently from one coach to the next.

Kivi and Alexander (1997) note that one coach preferred to use both sets of drills

differently depending on the focus of the session. For instance, one coach implemented the drills

over shorter distances (e.g. –10-meters) to emphasize speed and ground force application on

speed days. In contrast, the same drills were used at the end of the warm-up on tempo days for

longer distances (e.g. – 20-meters) to shift focus towards holding good technique for longer

periods of time. Other coaches, however, used these drills as part of the tempo workout by

having them perform them for a given time or distance. Little research has been done in this area

to elucidate the most appropriate means by which these tools should be used, or if they should

even be used at all.

To the author's knowledge, only one study by Cappadona (2013) has explored this

concept. This investigation aimed to identify the kinematic similarities and differences between

the Mach drills (i.e. – A-skip and B-skip) and maximal sprinting in collegiate-level sprinters. To

make this comparison, the investigator placed 24 reflective markers on the participants' upper

and lower bodies and captured their movements using 3D motion analysis cameras. Each

participant performed two trials of 40-meter sprints, two trials of 15-meter A-skips, and two

trials of 15-meter B-skips. Upon comparing the mechanics of each drill with those seen during

the 40-meter sprints, both the A- and B-skip yielded statistically significant differences in joint

kinematics. Specifically, the maximal sprint efforts yielded higher maximum hip flexion and a

significantly higher ankle angular velocity in comparison to the A-skip. Moreover, B-skips displayed significantly lower hip and knee flexion, lower maximum hip angular velocity, and higher ankle angular velocity. Based on these findings, it is quite clear that the premise on which the use of sprint drills is founded upon is flawed, as A-skips and B-skips do not mimic the movement patterns experienced in sprinting as closely as what some practitioners may believe.

A reason explaining this disconnect between sprint drills and the task may reside within the fundamental relationship between kinematics and kinetics. Essentially, movement outcomes are the result of both kinematic and kinetic parameters that govern the task (Jaric, Ristanovic, & Corcos, 1989). In other words, kinetic variables, such as GRF during a sprint, likely play a role in the outcome of biomechanics. Accordingly, drills that are used to rehearse or mimic the biomechanics of a task may not transfer when performing the skill if they lack the kinetic specificity of the task. This is not to say that sprint drills are not useful in any sense. Rather, they may be useful in attaining other objectives such as teaching fundamental movement concepts and reacquiring muscular tone in the latter portion of the warm-up. Although it is often overlooked, regaining muscular tone prior to training is crucial to performance, as stretching protocols used to increase an athlete's range of motion during a warm-up likely diminishes contractile filament cross-bridging (Jahnke, Proske, & Struppler, 1989). With less cross-bridging occurring between actin and myosin, an athlete's ability to produce force may be compromised during training. To combat this negative effect, sprint drills may be used as a means to "take out the slack" out of the muscle by restoring these cross-bridges and increasing muscle spindle sensitivity (Jahnke et al., 1989). With that said, practitioners should be cautious with the intent for which they use sprint drills due to the lack of kinematic and kinetic specificity to the task of sprinting.

Ultimately, sprint acceleration is a complex skill that can be developed through the use of multiple training methods. In contrast to this point, not all of these training strategies are created equal, as the efficacy of some are more supported in the literature than others. Therefore, understanding the kinematic, kinetic, and physiological mechanisms governing this skill will further clarify the best practices to develop sprint acceleration. Once a thorough understanding of these concepts is fostered, practitioners will be equipped select and integrate speed development tactics within the training process for different athlete populations and levels of ability.

<u>Acceleration Kinematics and Characteristics</u>

Historically, the acceleration phase of sprinting has been divided into multiple sub-sections. For example, Mackala et al. (2015) referred to these phases as "starting acceleration" (0-12m), "main acceleration" (12-35m), and in the case of elite sprinters, the "third transition" prior to reaching maximum velocity. Mann (2013), on the other hand, differentiates this phase into "the start" (steps 1-2), "the transition" (steps 3-10), and "maximum velocity". Regardless of how each sub-section is characterized, the concept of differentiating the acceleration phase into separate "zones" is not a recent development.

While some coaches may argue that this delineation is redundant, the rationale for doing so is based on differences in movement patterns inherent to each acceleration zone. In fact, a number of studies have suggested that the acceleration phase can be separated into multiple sub-sections based on biomechanical differences and alterations in sprint characteristics (e.g. – SL, SF, GCT, etc.) (Barr, et al., 2013; Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013; Mackala, 2007; Mann, 2013; Nagahara, Matsubayashi, et al., 2014; Nagahara, Naito, Morin, & Zushi, 2014; Rabita et al., 2015). While each athlete possesses unique biomechanical nuances,

deviations in sprint characteristics appear to be more quantitative than qualitative, as similar

trends are consistently displayed in the literature regardless of sprint ability (Nagahara, Naito, et

al., 2014).

This concept was highlighted in a study by Nagahara, Matsubayashi, et al. (2014) who

demonstrated that the acceleration phase could be separated into "initial-acceleration", "mid-

acceleration", and "transition" periods during a maximal effort 60-meter sprint. For example, the

athletes displayed rapid increases in hip extension velocity while applying high GRF behind the

center of gravity (COG) during their first 3 steps, which was characterized as the initial

acceleration zone. These movements were also accompanied by a swift elevation of the COG

and hips, as step length (SL) and step frequency (SF) increased exponentially to promote greater

sprint velocities. Most notable, however, was the fact that the participants exhibited no knee

flexion during ground support over these first few steps. That is, the sprinters began each trial by

utilizing a "pushing motion" as a means to increase movement frequency. After the first 3-steps,

the authors concluded that the kinematics began to show significant changes, which marked the

beginning of the mid-acceleration zone. Specifically, the participants began to exhibit increased

knee flexion during the support phase. This likely resulted from the athletes striking the ground

further in front of the body. In addition, the rate of elevation in the COG began to slow down,

while knee extension velocity rapidly increased up until approximately step 8. After this point,

the transition to maximum velocity consisted of further increases in sprint speed, which was

attributed to greater SL. This was likely caused by greater contribution from the shank during the

anterior support phase and the foot during the posterior support phase, as the range and velocity

of hip motion slightly decrease during this time period. Consequently, the differences in sprint

characteristics observed during acceleration are likely underpinned by different movement strategies within each zone.

When combined with the findings of other investigations, it can be argued these movement strategies can be characterized as "proximal-to-distal" in nature (Bezodis, 2009; Jacobs & van Ingen Schenau, 1992; Kugler & Janshen, 2010). More specifically, the early acceleration period seems to be more dependent on the proximal musculature of the hip and thigh (Bezodis, 2009; Jacobs & van Ingen Schenau, 1992), while the mid-acceleration period displays significant contributions from both the hip and lower leg (Nagahara, Matsubayashi, et al., 2014). Finally, the late-acceleration and maximum velocity phases often display the greatest contributions from the lower leg, as the foot must aggressively strike the ground in a "backwards" motion to deliver high GRF in close proximity to the sprinter's center of mass (COM) (Gittoes, Bezodis, & WIlson, 2011; Hunter, Marshall, & McNair, 2004; Mann, 2013). Accordingly, the gradual rise of the COG at greater sprint speeds discussed by Nagahara, Matsubayashi, and colleagues (2014) is likely influenced by the force-producing capabilities of the hip, thigh, and lower-leg musculature. Furthermore, these muscles may also be the "driving force" catalyzing a series of sequential changes in sprint characteristics during acceleration.

This concept has been described in a number of different studies (Barr et al., 2013; M. Coh, Milanovic, & Kampmiller, 2001; Debaere et al., 2013; Mackala, 2007; Mann, 2013; Morin et al., 2012; Nagahara, Matsubayashi, et al., 2014; Nagahara, Naito, et al., 2014; Rabita et al., 2015). For example, during the initial acceleration period, GCT is often at its peak, while flight time (FT) values are at a minimum (Barr et al., 2013; Coh et al., 2001; Mann, 2013; Nagahara, Naito, et al., 2014; Rabita et al., 2015). A similar antagonistic relationship exists between SL and SF, as SF usually shows a rapid increase towards maximum values, while SL measures are

minimal at this point (Mackala, 2007; Mann, 2013; Nagahara, Naito, et al., 2014; Rabita et al.,

2015). As the athlete transitions into mid-acceleration, GCT declines as FT is elevated with

greater sprint velocities (Barr et al., 2013; Debaere et al., 2013; Nagahara, Naito, et al., 2014;

Rabita et al., 2015). SF typically reaches its maximum and may show a slight decline before

stabilizing at a constant rate, while SL continues to gradually increase with greater displacements

(Debaere et al., 2013; Mackala, 2007; Nagahara, Naito, et al., 2014; Rabita et al., 2015). Finally,

as sprint speed approaches maximum velocity during the late acceleration period, SF stabilizes,

SL and FT approach maximum values, and GCT continues to decrease (Coh et al., 2001;

Debaere et al., 2013; Mackala, 2007; Mann, 2013; Nagahara, Naito, et al., 2014; Rabita et al.,

2015). This relationship is illustrated in Figure 2.1.
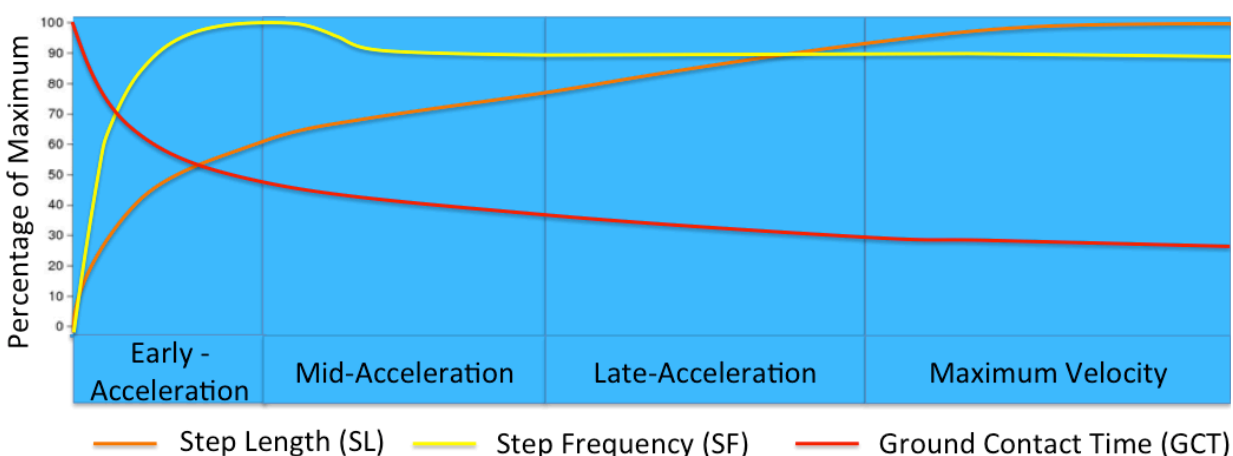
Figure 2.1 The evolution of sprint characteristics from acceleration through maximum velocity.

Concept based on findings of Mackala et al. (2007), Mann (2013), Nagahara, Matsubayashi, et

al., (2014), Nagahara, Naito, et al., (2014), and Rabita et al. (2015)

It is important to note, however, that the distances associated with these sprint phases

varies in accordance with the ability of the athlete, as better sprinters can accelerate for longer

distances in route to greater sprint velocities (Barr et al., 2013; Bruggerman & Glad, 1990;

Mackala et al., 2015; Mann, 2013). Additionally, the findings of Nagahara, Matsubayashi, et al., (2014) also suggest that sprint characteristics are, to a certain extent, relative to each athlete. This is likely due to a host of individual differences such as anthropomentric profiles (Mann, 2013; Rahmani, Locatelli, & Lacour, 2004), muscle fiber-type distribution (Trappe et al., 2015), and variations in the ability to express force (Alexander, 1989; Bret et al., 2002). It should come as no surprise that while Nagahara, Matsubayashi, and colleagues (2014) found similar spatiotemporal profiles between athletes, the acceleration zones defined in this study required a sizeable range. With the exception of the initial acceleration zone (steps 1-3), mid- and late-acceleration periods range from approximately steps 5-15 and steps 16-28, respectively. Unfortunately, this makes matters even more convoluted with respect to applying this information to field sport athletes.

Despite the insightfulness of these findings, the application to field sports should be approached cautiously, as the data previously presented were derived from populations of trained sprinters who began each effort from starting blocks. A comparison between these populations may be problematic for a few different reasons. The most obvious issue is that field sport athletes do not accelerate from starting blocks. Rather, they often begin sprint efforts from a variety of positions such as a crouched start, athletic stance, walking, jogging, or running. Therefore, it is feasible that they could display different sprint characteristics when compared to those previously discussed. This trend is noticeable in the little research that has been done comparing kinematic differences in "fast" and "slow" field sport athletes.

For example, Murphy et al. (2003) compared sprint kinematics in "fast" versus "slow" field sport athletes during steps 1 and 3 of the initial acceleration period from a staggered start position. The results revealed that the SL of faster participants was not statistically greater than

their slower counterparts. In contrast, the faster sprinters reached greater sprint velocities by means of producing statistically greater SF and abbreviated GCT. Similar results were found by Hewit and colleagues (2013), who investigated acceleration kinematics in national-level netball players during a 2.5-meter acceleration from an "athletic stance" starting position. The faster athletes of the group actually produced statistically shorter SL in comparison to the slower group. Surprisingly, SF was not statistically different between groups, but was still higher in the faster participants. When comparing early acceleration kinematics with those found in track and field athletes, faster sprinters seem to achieve greater sprint velocities by different means.

In a study by Slawinski et al. (2010), faster track and field sprinters reached higher sprint velocities during step 1 by displaying statistically greater SL over longer GCT. While not statistically different, SF was actually lower in the faster athletes. The opposite was true, however, when the sprinters reached step 2, as the faster sprinters progressed to higher velocities by increasing SF, as SL was no longer statistically different between groups. Along those same lines, the faster athletes also displayed shorter GCT in comparison to the slow group at this time point. Similar trends in the early acceleration period have been described by Coh and Tomazin (2006), Harland and Steel (1997), and Mann (2013). These authors explain that the increase in stride length during block clearance and step 1 are likely attributed to the fact that starting blocks allow sprinters to achieve steeper torso angles, which likely allows them to project their COM a greater distance. Kugler and Janshen (2010) also remind us that faster sprinters use this greater anterior lean of the torso to deliver greater propulsive GRF. Furthermore, this greater lean of the torso probably allows faster sprinters to accelerate for a longer period of time before reaching maximum velocity. Ultimately, the difference in starting position greatly affects the resulting sprint kinematics between populations during the early acceleration period. As the athletes

accelerate over greater distances, however, sprint kinematics become increasingly similar these populations, which suggests that the basic tenants of acceleration are constant between populations.

This concept was illustrated in a recent study by Barr et al. (2013) examining the sprint characteristics in rugby union players during a 50-meter sprint. The variables observed included SL, GCT, SF, and FT at the 3-meter, 9-meter, 15-meter, 21-meter, 33-meter, 39-meter, and 50-meter marks. Not surprisingly, each of these characteristics at 3-meters was significantly different from every other segment measured. Specifically, the 3-meter portion of the sprint encompassed longer GCT, shorter SL, and shorter FT in comparison with every other checkpoint. When comparing these qualities with those seen at 9-meters, sprint kinematics showed significant differences, as GCT became shorter while SL and FT became longer. In addition, SF measures reached maximum values. These maximum values were maintained at through the 15-meter mark. While SL continued to increase through this time point, it was not statistically different from SL at 9-meters and was also accompanied by further decreases in GCT. Lastly, it is also important to note that every athlete reached 96% of his maximum velocity by the 21-meter mark. Based on this information, the authors came to two major conclusions. First, the investigators suggest that the differences in sprint characteristics at 3-meters, 9-meters, and 15-meters serve to characterize these zones as the early-, mid-, and late phases of acceleration, respectively. Additionally, these results also indicate that the rugby athletes afforded greater sprint velocities by gradually increasing SL, maintaining near maximal SF, and rapidly reducing GCT, particularly in the mid- and late-acceleration zones. These results bear a striking resemblance to those displayed in Figure 2.1. Accordingly, it can be postulated that field

sport athletes likely display similar spatiotemporal trends during these segments in comparison to track and field athletes.

The potential underlying mechanisms that may explain this similarity may have been described by both Murphy et al. (2003) and Mann (2013). Particularly, one of the key kinematic differences between fast and slow field sport athletes as described by Murphy and colleagues (2003) was that faster sprinters did not display full knee extension prior to the foot leaving the ground at the end of each step. This characteristic is also supported by Mann (2013) in elite level sprinters. Combining this information with the fact that faster sprinters display greater horizontal velocity of the COM (Slawinski et al., 2010), it can be hypothesized that these superior velocities may not allow full extension of the trail leg prior to toe-off. Theoretically, this may lead to abbreviated GCT and an earlier initiation of stride recovery, or "swing time", in preparation for subsequent steps. It is important to note, however, that swing time does not seem to differ greatly between fast and slow sprinters (Weyand, Sternlight, Bellizzi, & Wright, 2000). In other words, fast and slow sprinters reposition their legs at similar rates between strides. Although sprinters of different capabilities display similar swing times, the mechanical positions achieved during flight time are quite different between these groups. Specifically, faster sprinters typically exhibit greater peak hip flexion during stride recovery prior to striking the ground during the next step (Clark & Weyand, 2014; Mann, 2013). Taking this into consideration, faster sprinters are likely to find themselves in a more advantageous position to "attack" the ground (DeWeese, Sams, et al., 2015) and make contact in closer proximity to their COM, a key component in achieving high propulsive GRF (Mann, 2013; Mero, Komi, & Gregor, 1992). Ultimately, these high GRF are the means by which faster athletes achieve greater sprint velocities (Clark & Weyand, 2014; Hunter et al., 2005; Kawamori, Nosaka, & Newton, 2013; Weyand et al., 2000). Therefore,

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differences in sprint kinematics may not necessarily be the key factor separating fast and slow sprinters. Contrary to this notion, these differences are likely a reflection of the athlete's ability to apply high forces over the brief GCT inherent to sprinting.

<div align="center">Acceleration Kinetics</div>

As mentioned in previous sections, movement patterns are governed by both kinematic and kinetic parameters (Jaric et al., 1989). Rather than viewing these factors as separate entities, it is important to understand that each plays a key role in producing coordinated movement. Keeping this concept in mind, differences in motor patterns are not just a reflection of biomechanical dissimilarities, but also a disparity in an individual's ability to produce force. When considered within the context of sprinting, differences in sprint mechanics are likely underpinned by an athlete's kinetic profile (DeWeese, Sams, et al., 2015; Morin et al., 2012; Rahmani et al., 2004). Specifically, strength-power variables such as impulse (IP), PF, and RFD directly influence an athlete's sprint mechanics by altering their ability to produce high GRF (Clark & Weyand, 2014; Hunter et al., 2005; Kawamori et al., 2013; Morin et al., 2012; Taber et al., 2016). This is significant because sprint velocity is ultimately limited by the amount of force an athlete can apply to the ground relative to their body mass (DeWeese, Sams, et al., 2015; Weyand et al., 2000).

This importance of GRF to sprint performance was clearly demonstrated in a foundational study by Weyand et al. (2000), who demonstrated the key differentiating factor between "fast" and "slow" runners was not the ability to rapidly reposition the legs between steps, but rather the ability produce higher GRF. This study pinpoints the ability to produce force as the limiting factor in sprint performance. Considering the importance of these findings, one

must also consider the underlying mechanisms contributing to the development of high GRF, particularly IP. IP can be described as the product of force and time (Taber et al., 2016). Specifically, IP describes the magnitude of force exerted over a given time period, such as the force delivered to the ground during the stance phase of sprinting. Essentially, greater levels of IP lead to higher GRF, which ultimately lead to greater sprint velocities.

This concept has been clearly shown in a number of studies in field sport athletes (Lockie et al., 2011; Lockie, Murphy, Schultz, Jeffriess, & Callaghan, 2013). Additionally, these studies not only support this notion, but also show the importance of generating large IP during the early (0-6 meters), mid- (6-12 meters), and late-acceleration (12-18 meters) periods, as proposed by Barr et al. (2013). For example, a study by Lockie et al. (2013) found moderate correlations between SL and vertical IP during in the first two steps of a 10-meter sprint. This is significant because SL also showed moderate correlations with sprint velocity during the first 5-meters of the sprint, thus showing the importance of generating high forces during the early acceleration period. With respect to the mid-acceleration period, Kawamori and colleagues (2013) examined the relationship between IP generated at the 8-meter mark during a 10-meter sprint in team sport athletes. The conclusions of this study revealed that the IP generated at this distance was also significantly correlated with 10-meter time. In addition, Hunter et al. (2005) found that field sport athletes displaying higher levels of propulsive IP relative to body mass reached faster sprint velocities at the 16-meters, thus confirming the significance of generating high forces in the late-acceleration period as well. Although the distances for each acceleration zone are different for track and field athletes, a number of studies also support the importance of developing high GRF to reach greater sprint velocities within this population as well (Clark & Weyand, 2014; Morin et al., 2012; Rabita et al., 2015). Despite the practical value of this information, it is important to

remember that faster athletes also display shorter GCT in comparison to their slower counterparts as well (Lockie et al., 2011; Mackala et al., 2015; Murphy et al., 2003; Weyand, Sandell, Prime, & Bundle, 2010).

When considered together, these differentiating factors reveal that faster sprinters achieve greater sprint velocities applying higher GRF at a faster rate than slower athletes. Stated differently, since faster athletes display shorter GCT, they have to develop force at a higher frequency to achieve the superior GRF underpinning greater sprint velocities. This conclusion was originally shown in another foundational study by Weyand et al. (2010), who found that the stance phase of sprinting is limited by the time over which forces can be applied, not the maximal forces applied to the ground. These findings were further supported in a recent study by Clark and Weyand (2014), who found that sprinters reached greater sprint velocities than non-sprinters by applying greater vertical forces during the first half of the stance phase. In fact, the authors described the force-time curve of the sprinters during ground contact as "biphasic" due to the rapid rise and early peak in force production. These athletes also displayed shorter contact times at sprint speeds of 3, 4, 5, 6, 7, and 8.1 meters per second. Lastly, similar results were also described by Morin and colleagues (2012), who determined that the primary mechanical determinant of a 100-meter sprinter is a "velocity-oriented" force-velocity profile. Stated differently, faster sprinters in the 100-meter event are those that express higher RFD during ground contact. Collectively, these findings support the notion of Stone et al. (2002) who suggest that RFD is perhaps "the most central factor to sport success".

While some may argue that P is the primary determinant of sport success (D. Baker, 2001a, 2001b; Bevan et al., 2010; Hawley, Williams, Vickovic, & Handcock, 1992), Taber and colleagues (2016) argue that RFD can be considered an underpinning mechanism of P (Figure

2.2). Specifically, greater RFD during a given time period leads to a greater IP, which is equivalent to momentum (M). Considering both of these variables contain the constituent components of P, RFD can be considered an underlying factor in determining the outcome of this variable. Therefore, regardless of terminology, it can be effectively stated that maximizing RFD is a primary objective with respect to enhancing sprint speed.
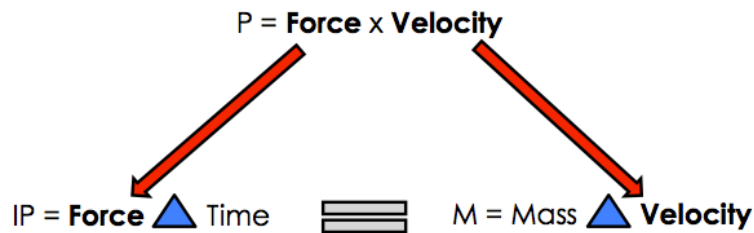
Figure 2.2 The relationship between impulse, momentum, and power

Physiological Underpinnings of Sprint Acceleration

With the fundamental understanding that speed is built upon strength characteristics, it becomes clear that the successful integration of these two entities is a primary objective in the training process. If this objective is met, the athlete has a strong chance of maximizing their performance capabilities at the appropriate time of the competitive season. If these qualities are not managed appropriately, the athlete may not realize the same level of preparedness prior to critical competitive events (DeWeese, Hornsby, Stone, & Stone, 2015b). Furthermore, in order to synergize strength and speed, practitioners must be able to harmonize a milieu of physiological and neurological adaptations. As previously mentioned in chapter 1, DeWeese and colleagues (2014a, 2014b) have proposed the use of SSI to fulfill this objective by merging the tenants of S2L, BP, and CSS. By creatively and strategically integrating these paradigms, the athlete may better realize critical performance qualities, such as RFD, at desired times of the training year.

The Short-to-Long Approach

Originally coined by the late Charlie Francis (1992), the S2L is a speed development methodology built upon the premise that faster top-end speeds are achieved by enhancing sprint acceleration. Theoretically, if an athlete can accelerate for a greater distance, they will likely reach greater sprint velocities, thus potentiating their top-end speed (Ross et al., 2001). In order to achieve this objective, coaches implementing this model prescribe shorter sprints at the beginning of the training year and progressively extend the distance of these efforts over time. From a training perspective, this structure is complimentary to BP, as the strength associates underpinning sprint acceleration and maximum velocity are developed in the same fashion within this paradigm. For example, acceleration has been related to an athlete's maximal strength levels and RFD in multiple studies (Bret et al., 2002; Comfort et al., 2012; Cunningham et al., 2013; Sleivert & Taingahue, 2004; Thomas et al., 2015), while maximum velocity has been more closely associated with RFD and stretch-shortening cycle (SSC) function (Mann, 2013; Morin et al., 2012; Sha, 2014; W. Young et al., 1995). With respect to the individual phases of acceleration, the author is unaware of any studies that have investigated the strength-power variables that govern each zone. With that said, a detailed examination of the adaptations garnered using BP may further elucidate the relevant kinetic qualities during the initial, mid-, and late-acceleration zones. However, before these adaptations can be viewed within the context of sprint acceleration, it is necessary to first understand the basic tenants of BP.

Block Periodization, Conjugate Sequential Sequencing, and Phase Potentiation

BP has been defined as "the logical, phasic method of manipulating training variables in order to increase the potential for achieving specific performance goals" (Stone, Stone, & Sands, 2007). The overall goals of this framework are to effectively manage fatigue and maximize

important performance qualities, such as RFD and PP, at critical times of the training year. Essentially, BP can be thought of as a "blueprint" that outlines the development of fitness phases over a particular timeline. Programming, on the other hand, refers to the strategies used within this structure (e.g. – sets and reps) to elicit a desired response (Stone, Stone, & Sands, 2007). It is important to distinguish the difference between these two terms, as they each serve different purposes in the training process.

Traditionally, BP has been structured into periods of "accumulation", "transmutation", and "realization" (Bompa & Haff, 2009; DeWeese, Hornsby, et al., 2015b; Issurin, 2008; Stone, Stone, & Sands 2007). While there is often overlap between these phases and the fitness characteristics inherent to each of them, these periods typically coincide with the development of strength endurance (SE), maximal strength (MS), and RFD, respectively (DeWeese, Hornsby, et al., 2015b; Harris, 2000; Painter et al., 2012; Stone, Stone, & Sands, 2007). A number of studies have shown that sequencing fitness characteristics in this fashion is an effective method of maximizing P (Harris, 2000; Painter et al., 2012; Zamparo, Minetti, & di Prampero, 2002). This is significant because athletes who express greater P, and subsequently RFD, are likely to achieve greater sport success (Baker, Nance, S., 1999; Haff & Stone, 2015; Stone, Moir, Glaister, Sanders, 2002). This sequence is likely successful due to the different rates of decay of each fitness characteristic, as the adaptations from the accumulation and transmutation phase display a longer half-life than those in the realization phase (Issurin, 2008). Consequently, residual training effects from these phases likely serve to enhance or "potentiate" the adaptations in the subsequent training periods, which is referred to as "phase potentiation" (Bompa & Haff, 2009; DeWeese, 2015; DeWeese, Sams, et al., 2015; Issurin, 2008; Stone, Stone, & Sands,

2007). Despite the value of this model, there are still key limitations that need to be considered over the course of the training year.

Most notably, there has been an exponential increase in the number of competitions per training year in recent decades, which has inherently diminished the time an athlete can dedicate towards training (Issurin, 2008). This decrement in training time will likely compromise the stability of the physiological adaptations garnered during the accumulation and transmutation periods (Issurin, 2008; Stone, Stone, & Sands, 2007). Consequently, the athlete is susceptible to physiological involution during the competitive period, as the adaptations from the previous training phases erode prior to reaching peak performance (Bompa & Haff, 2009; Issurin, 2008; Stone, Stone, & Sands, 2007). From a physiological standpoint, this is likely due to prolonged reductions in resistance training volume, which can result in diminished muscle cross-sectional area (CSA) and subsequent decrements in RFD and P (Stone, O'Bryant, Schilling, & Johnson, 1999; Stone, Stone, & Sands, 2007). To avoid this pitfall, a variety of programming tactics have been adopted into modern day BP to attenuate this decay in fitness and preserve phase potentiation. Often referred to as CSS, these strategies primarily include utilizing concentrated loads, retention loads, and functional overreaching (Bompa & Haff, 2009; DeWeese, Hornsby, Stone, & Stone, 2015a; DeWeese, Hornsby, et al., 2015b; DeWeese, Sams, et al., 2015).

Concentrated loads are defined as brief periods of time in which a specific fitness characteristic is emphasized (DeWeese, Sams, et al., 2015; Stone et al., 1999; Stone, Stone, & Sands, 2007). This loading scheme is generally implemented for periods of approximately 4 to 8 weeks (DeWeese, Hornsby, et al., 2015b; Stone et al., 1999; Stone, Stone, & Sands, 2007). Each week within this time period is typically referred to as a "microcycle", while the whole time interval is referred to as a "mesocycle" or "block" (DeWeese, Hornsby, et al., 2015b; Issurin,

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2010). When successive microcycles are linked together, they are commonly called "summated microcycles" (DeWeese, Hornsby, et al., 2015a, 2015b; Stone, Stone, & Sands, 2007). These are important concepts with respect to accumulating fitness characteristics, as summated microcycles are utilized to apply a concentrated load over the course of a block to facilitate a desired training response. Similar to summated microcycles, summated blocks of concentrated loads have shown been shown to provide superior training adaptations in comparison to the traditional, multi-directional loading scheme (Verkhoshansky, 1985). When combined with proper sequencing of fitness characteristics, the summated effects of concentrated loads may further bolster phase potentiation (DeWeese, Hornsby, et al., 2015b; Verkhoshansky, 1985). With respect to short-term adaptation, brief periods of marked increases in training volume or intensity, or "functional overreaching", can also be used to facilitate a delayed training effect in the subsequent 2 to 5 week period (Stone et al., 1991b). Stated differently, the functional overreach likely provides a short-term potentiation effect following a period of adequate restitution. Even more important, however, this strategy can be used to re-establish fitness characteristics from previous training blocks, thus deterring training involution and "bleeding" the adaptations from one training phase into the next (Bompa & Haff, 2009).

While the combination of CSS and BP pave the road to phase potentiation, improvements in performance are ultimately driven by a defined sequence of training adaptations. Verkhoshansky (1985) defines this sequence as "relatively predictable" and further explains that individual variation from this structure is more "quantitative" than "qualitative". In other words, the adaptations experienced during the accumulation, transmutation, and realization periods are fairly consistent from one person to the next. Therefore, understanding of how the interplay

between these adaptations impacts performance is paramount in successfully integrating BP with S2L.

Integrating the Short-to-Long Model within Block Periodization: The Accumulation Phase

As previously stated, BP is generally composed of 3 phases: accumulation, transmutation, and realization. The accumulation stage typically consists of higher training volumes at lower intensities and is often implemented during the general preparatory period (GPP) (Bompa & Haff, 2009; Issurin, 2008). The primary objectives of this training phase are to increase work capacity, improve body composition, and increase CSA (DeWeese, Hornsby, et al., 2015b; Issurin, 2008; Zatsiorsky & Kraemer, 2006). Enhancing work capacity and body composition may better prepare the athlete to handle more rigorous training intensities in subsequent training phases. From a physiological standpoint, these objectives likely result from a shift in the myosin heavy chains towards the type IIa phenotype (Adams, Hather, Baldwin, & Dudley, 1993) and greater mobilization of free fatty acids in the post-training period, which is likely catalyzed by increased serum levels of growth hormone, insulin-like growth factor-1, and testosterone (Kraemer, 1992a; Kraemer et al., 1990). Similarly, the increases in CSA may also prepare the athlete to handle higher training intensities, as the CSA of a muscle fiber has been directly related to the magnitude of force it can produce (Cormie, McGuigan, & Newton, 2011). This morphological adaptation ultimately results from increased protein synthesis, which may be attributed to a rise in the muscular tension, damage, and metabolic stress associated with resistance training (Allen, Roy, & Edgerton, 1999; Goldspink, 1999; Schoenfeld, Aragon, & Krieger, 2013; Zanchi & Lancha, 2008). Additionally, increases in hypertrophy are commonly accompanied by important architectural changes to the muscle such as greater angles of pennation (Kawakami, Abe, & Fukunaga, 1993; Kawakami, Muraoka, Kubo, Suzuki, &

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Fukunaga, 2000). This structural alteration likely results from the addition of sarcomeres in parallel alignment (Goldspink, 1999). This is significant from the perspective of muscle function in that this alignment has been show to increase the muscle's ability to produce force (Goldspink, 1999). With that said, increased force production is likely catalyzed by alterations to the central nervous system (CNS), as these adaptations appear to precede morphological alterations (Moritani & deVries, 1979; Seynnes, de Boer, & Narici, 2007; Siff, 2009).

Prior to discussing the neurological adaptations associated with the accumulation phase, it is important to understand how training volume impacts neurological function. Regardless of the type of training (e.g. – resistance training, sport activity, etc.), both acute and chronically elevated workloads may lead to an accumulation of neuromuscular fatigue and subsequent decrements in performance (Barker et al., 1990; Flanagan et al., 2012; Fry, 1998; Kuipers, 1996; Marshall, McEwen, & Robbins, 2011; Smith, 2000). This is not to say that periods of higher training volumes are unnecessary, as greater workloads are required to foster the muscular adaptations previously discussed. However, if the associated fatigue is not effectively managed, high training loads may lead to diminished RFD (Flanagan et al., 2012; Marshall et al., 2011) and decreased motor control (Barker et al., 1990), both of which are primarily governed by the CNS (Stone, Stone, & Sands, 2007).

While the precise mechanisms of CNS fatigue remain inconclusive, performance decrements may be attributed to a variety of causes including decreases in resting membrane potential (Gardiner, 1991), sarcolemma conductance (Ross et al., 2001), dendritic branching (Chen et al., 2009), soma size (Gardiner, Dai, & Heckman, 2006), size of the neuromuscular junction (Deschenes et al., 2000), neurotransmitter and receptor concentrations (Gardiner et al., 2006), and axon diameter (Gardiner et al., 2006). There is also evidence suggesting that higher

training volumes may lead to excessive cortical activity, which may possibly accumulate greater levels of fatigue and decrease P (Flanagan et al., 2012). Although these maladaptations are contradictory to the end goal of maximizing RFD, the high-volumes of training during the accumulation phase are implemented long before the competitive season. Therefore, these decrements in neurological capabilities are not the primary concern during this time of the training year.

One may argue that this rationale is similar to those endorsing a Long-to-Short (L2S) approach, where longer sprint distances are used to accumulate greater work capacity early in the training year (DeWeese, Sams, et al., 2015). Despite these similarities, the increased work capacity developed in the S2L model is quite different from that of the L2S, as the means to acquire this fitness characteristic are completely separate. Although training loads are high in both methodologies, the SE in the S2L is developed using higher volumes of resistance training, whereas the L2S typically develops this quality by increasing sprint distances. Consequently, the physiological ramifications of each training tactic could not be more different from the other. For example, the resistance training used to develop work capacity in the S2L is typically performed at a level of intensity that upregulates protein synthesis, primarily through the mTOR pathway (Egerman & Glass, 2014). These physiological events lead to increased muscle CSA, thus creating a foundation for improved MS and RFD (Stone, Stone, & Sands, 2007; Zamparo et al., 2002). In contrast to this sequence of events, increased training volume with longer sprint distances will likely have a different physiological impact (Ross & Leveritt, 2001). Rather than up-regulating the mTOR pathway, longer sprints will likely decrease the ATP-to-ADP ratio, thus increasing the activation of the AMPk pathway (Nader, 2006). Not only is this mechanism antagonistic to mTOR signaling, but it can also lead to muscle atrophy by activating E3 ligases,

such as MuRF-1, and FOXO proteins (Egerman & Glass, 2014; Lecker, Goldberg, & Mitch, 2006). These agents play key roles in facilitating the Ubiquitin-Proteasome pathway, which is a primary source of protein degradation (Lecker et al., 2006). Furthermore, recent literature has also suggested that hypertrophy is non-uniform and highly specific to motor unit activation (Wakahara, Fukutani, Kawakami, & Yanai, 2013). In other words, high-volumes of work at low-intensities will likely recruit lower-threshold motor-units (Henneman, Somjen, & Carpenter, 1965), thus causing hypertrophy of type I fibers (Meijer et al., 2015) and potentially shifting the myosin heavy chains of type II fibers towards the type I phenotype (Ross & Leveritt, 2001). It has also been hypothesized that the presence of more type I fibers may cause a "dampening effect" on the contractile velocity of type II fibers as well (Bosco et al., 1982).

Subsequently, although high volumes of resistance training will likely inhibit the nervous system's ability to produce high RFD, the work capacity and hypertrophy of type II fibers garnered within this time period are essential to potentiating the athlete's MS development in future blocks (Minetti, 2002; Zamparo et al., 2002). As Stone and colleagues (2007) remind us, MS is the fitness quality underpinning superior gains in RFD and PP in future training phases. When viewed from this perspective, the accumulation phase can be thought of as a "down payment" on future increases in these critical performance variables. With respect to sprinting, however, this adaptive process should not adversely effect the development of acceleration, as this skill seems to follow a predictable set of sequenced events.

More specifically, it has been suggested that an early adaptation to sprint training is acquiring a greater anterior lean of the torso, particularly during the first two steps of acceleration (Spinks et al., 2007). As Kugler and Janshen (2010) remind us, an increased inclination of the torso is critical because it puts the athlete in an advantageous position to deliver

higher propulsive GRF. Fortunately, several investigations have suggested that sled towing may be a useful training tactic to develop this particular quality (Letzelter, Sauerwein, & Burger, 1995; Lockie et al., 2003; Spinks et al., 2007). Most notably, a study by Spinks and colleagues (2007) found an 8-week sled-towing program to facilitate greater lean of the torso in the early acceleration zone in field sport athletes. In addition to these findings, Letzelter (1995) and Lockie (2003) have also suggested that the increases in trunk lean may be influenced by increases in sled towing resistance. While an in increase in GCT with greater external loads is likely, this may actually benefit the athlete by providing a longer period of time to produce force, thus compensating for the diminished RFD from higher volumes of resistance training. Additionally, the resulting increases in CSA and angles of pennation from those higher workloads may also facilitate an improved ability to handle the greater loads required to reach a steeper anterior lean of the torso.

Similar to sled towing, incline sprinting may also be a valuable method in improving sprint acceleration during the accumulation phase, as this training modality may also minimize the deleterious effects from high volume loads. For example, Gottschall and Kram (2005) showed that incline running on an angle of 9 degrees displayed statistically lower impact loading rates upon ground contact and statistically greater propulsive GRF in comparison to running on a level surface. This trend was also evident at 3 and 6 degrees as well, but at smaller magnitudes as the surface approached 0 degrees. The authors note that the decrease in impact loading rates was likely attributed to decreased landing velocity of the foot, as the distance between the participants' feet and the ground was shorter at greater inclines. In other words, the participants did not have to absorb the same high loading rates experienced in flat-ground sprinting, potentially reducing the role of RFD during the stance phase while running uphill. Gottschall and

Kram (2005) also hypothesized that this abbreviated footfall necessitated an increase in leg stiffness to maintain propulsive GRF. While these methods may enhance the athlete's sprint capabilities during the early acceleration period, developing increased leg stiffness may also serve as a means to produce higher RFD in subsequent training phases as the sprint distances are lengthened.

Although these adaptations are best suited to develop the early acceleration phase, it may also be beneficial to briefly introduce the athlete to the mid- and late-acceleration zones as well. Conceptually, this strategy is similar to CSS in that multiple training components are addressed simultaneously, but with varying degrees of emphasis. For example, the concentrated load for a particular block would represent the primary stimulus, while less significant points of emphasis may serve as secondary and tertiary stimuli, respectively. When put in the context of speed development, this concept is often referred to as "vertical integration" (Francis, 1992) and may assist in the proper sequencing of acceleration development. For example, early acceleration can be made the primary point of emphasis by implementing a concentrated load specific to this objective. Although they are not as emphasized, the mid- and late-acceleration zones can also be addressed to a lesser extent as secondary and tertiary objectives within this timeframe as well (Figure 2.3). When combined, BP, CSS, and vertical integration may provide an avenue to simultaneously potentiate both speed and strength characteristics from one training phase to the next.
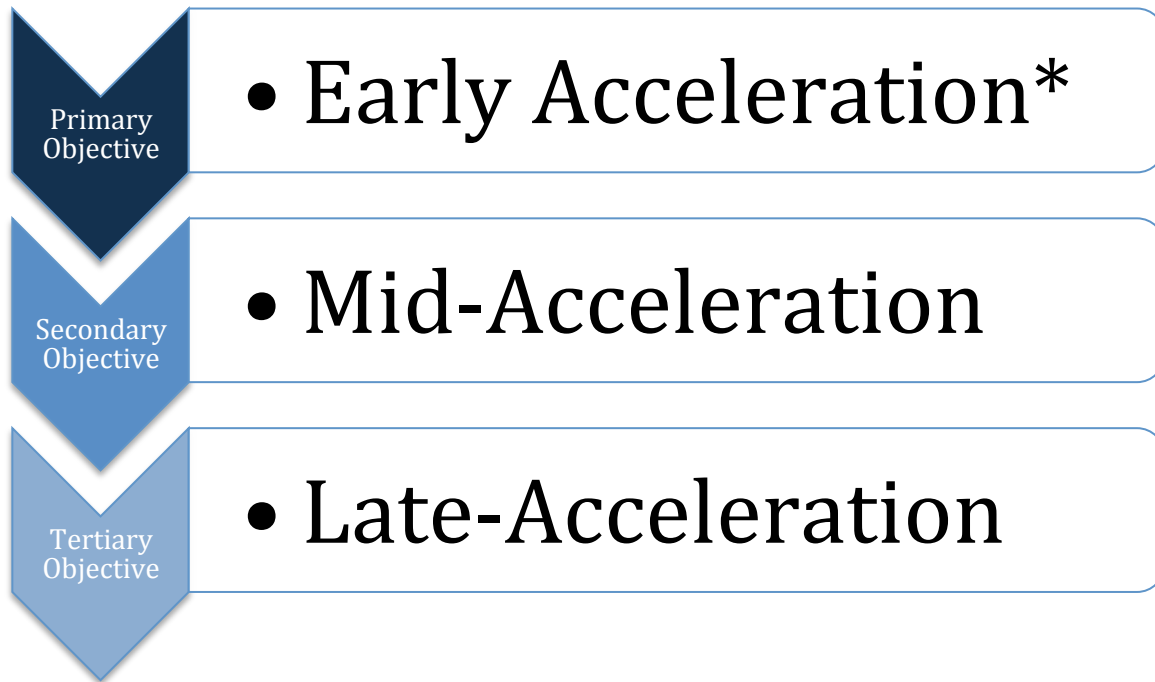
* = Concentrated Load

Figure 2.3 Acceleration development during the accumulation phase

Integrating the Short-to-Long Model within Block Periodization: The Transmutation Phase

Following the accumulation phase, the focus of training transitions towards enhancing MS during the transmutation period. This purpose is often achieved by decreasing resistance training volume and increasing intensity (Harris, 2000; Hornsby, 2013; Painter et al., 2012). This shift typically occurs during the transition from the GPP to the specific preparatory period (SPP) (Bompa & Haff, 2009). As previously mentioned, an athlete's MS is the foundation upon which RFD and P are built (Andersen & Aagaard, 2006; Cormie et al., 2011; Stone, Stone, & Sands, 2007; Taber et al., 2016). As such, the significance of this training period cannot be overstated. Unlike the accumulation phase, the adaptations fueling further increases in MS are likely both physiological and neurological in nature.

In particular, the decrease in training volume coupled with increased intensity will likely cause a shift in the myosin heavy chains towards the type IIx phenotype (Ross & Leveritt, 2001). This change is crucial for three reasons. First, with more fibers transitioning towards the type IIx phenotype, the athlete will likely increase their type II to I fiber ratio (Hakkinen et al., 1998). Secondly, the fibers shifting in this direction may undergo further increases in CSA with higher training intensities (Froböse, Verdonck, Duesberg, & Mucha, 1993). Finally, the hypertrophy of these fast-contracting fibers will likely be accompanied by further increases in muscle angles of pennation (Goldspink, 1999). With these three morphological adaptations occurring in concert, the athlete will likely posses the means to adapt to greater training loads, which are vital to further developing the nervous system in the realization phase. While these structural changes are important, they can also be perceived as a reflection of enhanced neurological function as muscle fibers have been shown to adopt the characteristics of the motor neuron by which they are innervated (Buller, Eccles, & Eccles, 1960; Gardiner, 1991; Salmons & Vrbova, 1969). In a sense, the muscle fibers can be seen as a "slave to the nervous system".

Keeping this in mind, the neurological status of the athlete will likely begin to show progressive improvements, as the accumulated fatigue from the previous phase will likely begin to dissipate with the removal of high training volumes (Stone, Stone, & Sands, 2007). These improvements are in accordance with the fitness-fatigue paradigm, which states that the athlete's preparedness is defined as the summation of fitness and fatigue resulting from training (Zatsiorsky & Kraemer, 2006). If the accumulated fatigue from the previous training period was sufficiently managed, residual training effects may yield improvements in performance such as enhanced RFD (Hornsby, 2013; Painter et al., 2012) and P (Harris, 2000; Hornsby, 2013). Additionally, the higher training intensities implemented in this time period may also lead to

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greater recruitment of high threshold motor units (HTMU) (Henneman et al., 1965) and increased rate coding (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002), otherwise known as "neural drive".

From a mechanistic perspective, it has been suggested that higher training intensities may decrease the sensitivity of type Ib afferents, which may decrease neural inhibition (Aagaard, 2003). Additionally, greater training intensities may also decrease motor unit recruitment thresholds, particularly in high-threshold motor units (HTMU) (Desmedt & Godaux, 1977). This is very important from the perspective of enhancing RFD in that HTMU's display faster conduction velocity in comparison to their lower-threshold counterparts (Duchateau, Semmler, & Enoka, 2006). Furthermore, enhanced rate coding likely increases the frequency at which those HTMU's are activated (Aagaard, 2003). In other words, higher training intensities are not only likely to recruit a greater number of HTMU's, but these motor units may also be activated at a higher frequency. While the mechanisms responsible for improved rate coding remain unclear, the potential sources contributing to these adaptations may include increases in resting membrane potential (Gardiner, 1991), dendritic branching (Gardiner et al., 2006), soma size (Gardiner et al., 2006), size of the neuromuscular junction (Deschenes et al., 2000), neurotransmitter and receptor concentrations (Gardiner et al., 2006), and axon diameter (Gardiner et al., 2006). Despite the fact that maximizing RFD is not the primary purpose of this training phase, these neurological adaptations likely catalyze the development MS (Moritani & deVries, 1979; Seynnes et al., 2007; Siff, 2009), thus enhancing the athlete's ability to produce higher rates of force as well. This may better prepare the athlete to maximize this quality during the final phase of training and potentiate the adaptations in the subsequent blocks. Moreover,

enhancing the athlete's ability to produce high rates of force may translate to greater sprinting ability, likely occurring through decreases in GCT (Morin et al., 2012).

While the earliest adaptation to sprint training appears to be attaining a steeper anterior lean of the torso, the ability to minimize GCT appears to be a secondary adaptation (Barr, 2014; Murphy et al., 2003). In fact, shorter contact times may be a residual benefit from achieving a greater forward lean of the trunk during early acceleration. When revisiting the results of Spinks et al. (2007), an important finding to note is that although the athletes who participated in sled towing showed the largest improvements in anterior lean of the trunk, another group that took part in non-resisted sprint training also showed improvements in this quality as well, but to a lesser extent. These findings reinforce the notion proposed by Lockie et al. (2003) and Letzelter (1995) that the degree of trunk inclination achieved by an athlete may be related to the level of resistance applied while sprinting. When these results are considered in conjunction with that of Barr et al. (2013) and Murphy et al. (2003), it can be argued that as an athlete acquires a steeper trunk angle, they may realize a more advantageous position from which they can express force. If these positions are accompanied by progressive increases in RFD, the athlete may be able to develop greater propulsive GRF over shorter GCT (Morin et al., 2012).

This notion was clearly evident in the findings previously discussed by Morin and colleagues (2012). Recall that the investigators found a "velocity-oriented" kinetic profile to be a key mechanical determinant in 100-meter sprint performance. The authors elaborated that this characteristic likely accounted for greater "resultant GRF vectors with a forward orientation". Perhaps the most important finding, however, was higher SF was likely the result of abbreviated GCT. Stated differently, the expression of higher RFD may allow the athlete to generate greater propulsive GRF over shorter GCT, essentially forcing the athlete to express greater SF. This may

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also explain why faster sprinters often display abbreviated knee extension prior to toe-off, as Mann (2013) and Murphy et al. (2003) have previously described. Ultimately, when combined with a steeper trunk angle developed in the accumulation phase, the increases in RFD during the transmutation period may allow the athlete to "capitalize" on this training effect by producing higher propulsive GRF in a positive direction over abbreviated GCT. Similar to previous training blocks, the speed development strategies implemented in the transmutation stage should mirror the physiological status of the athlete.

While the tactics utilized during the accumulation phase seem most relevant to early acceleration, the adaptations during the transmutation period may provide the appropriate resources to segue into the mid-acceleration zone. As described by Barr et al. (2013), the increases in SV within this period are realized by: maximizing SF, decreasing GCT, and steadily increasing SL. When comparing these sprint characteristics to those seen in the early acceleration phase, the differences appear to be more quantitative than qualitative, as similar trends were described by Murphy and colleagues (2003) during the first three steps of acceleration. Therefore, similar speed development methods from the previous training phase may also be appropriate to incorporate at further sprint distances. However, additional adjustments to these methods may increase task specificity during this training period, as the SV in the mid-acceleration zone is likely higher than in early-acceleration (Barr et al., 2013). Therefore, decreasing sled towing resistance and using subtle inclines when sprinting uphill may be worthwhile considerations when addressing the mid-acceleration phase. Furthermore, these methods may be used to provide a concentrated load to emphasize this quality (Figure 2.4). While heavier sled towing loads and steeper inclines should be de-emphasized in this training phase, they may still be valuable in retaining the previously developed adaptations. Finally,

further exposure to the late acceleration zone may also benefit the athlete by introducing the primary training stimuli in subsequent training phase (DeWeese et al. 2015). Again, exploiting the concepts of BP, CSS, and vertical integration may further potentiate future adaptations during the realization phase.

Primary Ojbective	• Mid-Acceleration*
Secondary Objective	• Early Acceleration
Tertiary Objective	• Late-Acceleration
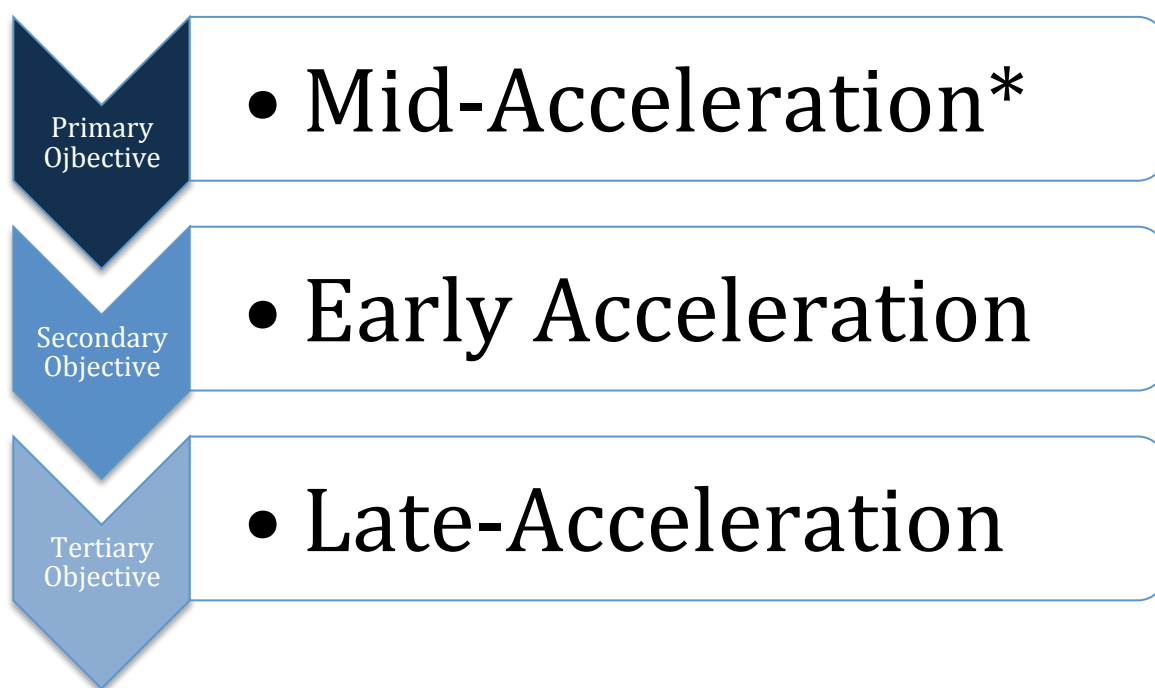
* = Concentrated Load

Figure 2.4 Acceleration development during the transmutation phase

Integrating the Short-to-Long Model within Block Periodization: The Realization Phase

The realization phase of BP is carried out during the competitive period (CP), where the primary objective is to maximize P, and subsequently RFD, prior to important competitive events (Issurin, 2008; Zatsiorsky & Kraemer, 2006). This purpose may be achieved by further increasing training intensity while simultaneously decreasing training volume (Harris, 2000; Hornsby, 2013; Painter et al., 2012). This is a critical task, as excessive training volumes will likely accumulate additional fatigue, which has been shown to severely hinder RFD (Barker et

al., 1990; Flanagan et al., 2012; Marshall et al., 2011; Stone, Stone, & Sands, 2007).

Accordingly, providing the athlete with a "minimum effective dose" of high intensity training is likely the best approach to heighten this fitness characteristic. For instance, prescribing low doses of high-load and low-velocity (HL) exercises, such as a back squat at >90% 1RM (Haff & Stone, 2015), and low-load and high-velocity (HV) exercises, such as jump squat (Baker, Nance, S., 1999), may elicit this desired training response. Additionally, high-load and high-velocity lifts (HLV), such as a mid-thigh power clean and other weightlifting movements, may also serve as an effective tool to fulfill this purpose as well (Haff & Stone, 2015). A number of studies have indicated that combination training using both HL and HV exercises produce greater gains in RFD and P in comparison to one of these methods in isolation (Haff & Nimphius, 2012; Harris, 2000; Painter et al., 2012; Stone et al., 1998). Theoretically, the combination of these methods allows the athlete to "saturate" the entire force-velocity curve, thus shifting both ends of this paradigm in a positive direction (Haff & Nimphius, 2012). Consequently, HL, HV, and HLV movements may be effective tools in developing superior RFD.

Similar to the transmutation period, additional reductions in training volume and increases in training intensity may facilitate morphological adaptations that can lead to greater PF, P, and RFD (Ross & Leveritt, 2001). Specifically, these training alterations will likely cause a shift in the myosin heavy chains further towards the type IIx phenotype (Ross & Leveritt, 2001), increase type II fiber CSA (Fröböse et al., 1993), and elevate the type II to type I muscle fiber ratio (Hakkinen et al., 1998). With that said, one must recall that these changes are likely preceded by neurological adaptations (Moritani & deVries, 1979; Seynnes et al., 2007; Siff, 2009). This concept is evident when revisiting the findings of Desmedt and Godaux (1977) who showed that higher intensities of resistance training tend to decrease motor unit recruitment

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thresholds. Even more important, however, is that the motor units with the highest thresholds showed the greatest decrease in recruitment threshold. Stated differently, HL exercises may serve to increase the activation of HTMU's, which could initiate the morphological alterations of the fibers associated with that motor unit (Buller et al., 1960; Gardiner, 1991; Salmons & Vrbova, 1969).

Despite the absence of higher resistance, HV exercises (e.g. – ballistic or explosive movements) may also play a key role in the activation of HTMU's. Specifically, rapid muscle contractions activate HTMU's earlier than slower contractions, and may also activate up to three times as many motor units in comparison to slower movements as well (Duchateau et al., 2006). Similar to HF exercises, HV movements seem to utilize more HTMU's by decreasing the recruitment threshold with training (Zehr & Sale, 1994) and could be accompanied by similar physiological adaptations, such as increase CSA of type IIx fibers (Froböse et al., 1993). The architectural adaptations, however, appear to be different, as explosive exercises appear to increase the number of sarcomeres in series rather than parallel alignment (Nimphius, McGuigan, & Newton, 2012). This is significant from the perspective of increasing RFD because this alignment tends to favor muscle fiber shortening velocity rather than force production (Maganaris, 2001).

HLV exercises likely offer most of the adaptations provided by HF and HV movements (DeWeese et al., 2016). These exercises typically include weightlifting (WL) movements such as the jerk, snatch, clean, power clean, and hang power clean (Haff & Stone, 2015). While many coaches argue that the weightlifting movements require too much time to teach, a strong argument can be made that the training efficiency of these exercises far outweighs the time required to learn the movements (DeWeese et al., 2016). Considering the importance of

prescribing the minimal effective dose of exercise, using a single WL exercise to foster a desired training effect is likely the more efficient training decision in comparison to prescribing two separate exercises, as often seen in post-activation potentiation complexes. Adding an additional exercise may accumulate higher training volumes thus defeating the primary objective of the training phase. This is not to say that potentiation complexes are inappropriate training tools. In fact, when appropriately implemented, they have been shown to effectively increase P (Tillin & Bishop, 2009). When put in the scope of the primary objective, however, the use of WL movements appears to be the most efficient method in achieving maximal RFD during this phase of training.

Considering the brevity of the foot contacts during the later phases of sprinting, maximal RFD must be expressed in order to develop the high GRF inherent to greater SV (DeWeese, Sams, et al., 2015). As this fitness quality is developed, the athlete may be better equipped to handle the demands of the late-acceleration and maximum velocity phases of sprinting (Mann, 2013; Weyand et al., 2010). Accordingly, the primary objective with respect to speed development is to allow the athlete to realize these adaptations at a further sprint distances. A potential issue in attaining this goal is that the athlete has to accelerate through the early- and mid-acceleration zones to reach greater SV. While this may allow the athlete to retain performance adaptations from previous blocks, it may also limit a coach's ability to adequately develop the final phase of acceleration, as this may quickly accumulate larger training volumes and neuromuscular fatigue. To address this issue, many coaches advocate drills that are intermittent in nature to develop the later phases of sprinting. For example, a drill commonly referred to as "ins and outs" requires the athlete to sprint maximally for a distance of 10-20 meters for the "in" portion and slow down to a submaximal pace for 5-20 meters of the "out"

portion (Ross et al., 2001). This cycle is typically repeated 2-3 times per repetition. This structure is believed to afford the athlete with the opportunity to activate HTMU's multiple times over the course of the drill and accumulate more training volume that is conducive to developing top-end speed (Ross et al., 2001). Theoretically, implementing these types of drills in combination with "full sprints" may provide a concentrated load specific to the late-acceleration and maximum velocity phases, as well as provide retaining loads for the previous acceleration periods as well.

In summary, by exploiting the fundamental concept that sprint speed is built upon strength-related qualities, the S2L model harmonizes an array training adaptations to develop peak sprint acceleration abilities at the appropriate times of the year (DeWeese, Sams, et al., 2015). By using BP, CSS, and vertical integration, the seamless sequential integration model aligns the sequential development of RFD with the demands of each acceleration zone. Despite the potential value of this model to field sport athletes, the specific kinetic demands inherent to each phase of acceleration have yet to be elucidated. While maximizing RFD is a primary objective in the training process, elucidating which kinetic variables are most prominent in each portion of the sprints may provide valuable information with respect to integrating strength training and speed development. This information may lead to greater training specificity and an enhanced transfer of training effect, thus further improving sprint performance.

Primary Objectvie • Late-Acceleration*

Secondary Objective • Mid-Acceleration

Tertiary Objective • Early Acceleration
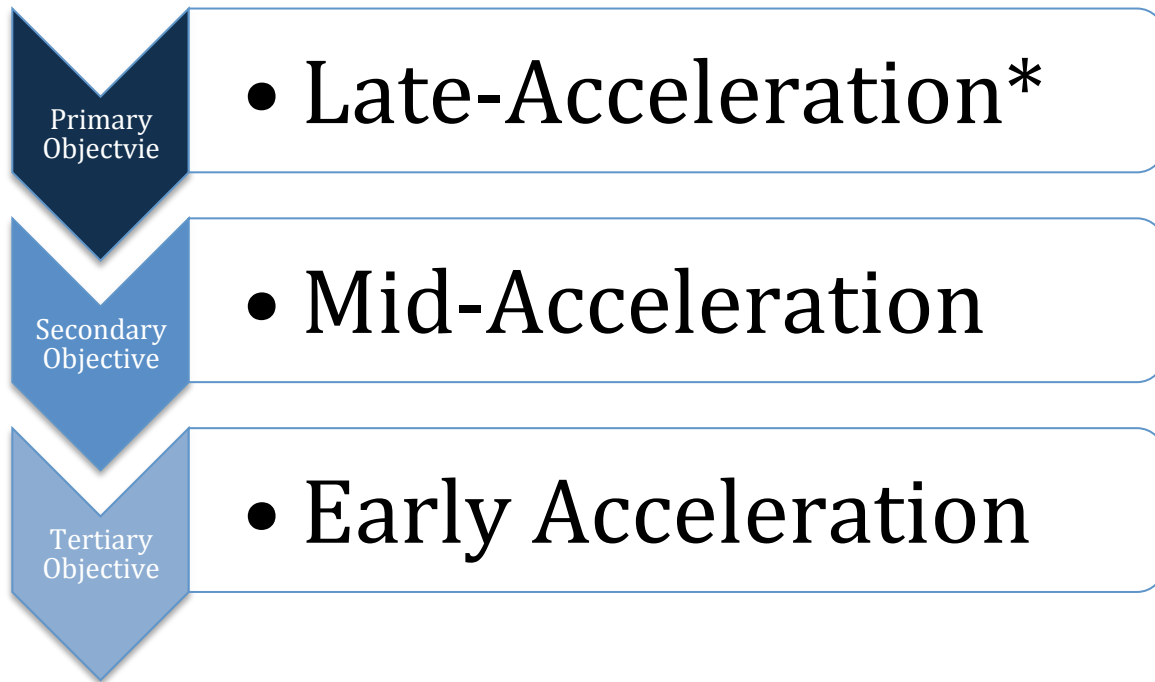
* = Concentrated load

Figure 2.5 Acceleration development during the realization phase

CHAPTER 3

DEFINING THE EARLY, MID, AND LATE SUB-SECTIONS OF SPRINT ACCELERATION
IN DIVISION I MEN'S SOCCER PLAYERS

Authors: [1]Christopher R. Bellon, [1]Brad H. DeWeese, [1]Kimitake Sato, [2]Kenneth P. Clark, [1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of

Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Kinesiology, West Chester University, West Chester, PA, USA

Abstract

Purpose: The purpose of this study was to investigate if the acceleration phase of sprinting can be divided into early, mid, and late sub-sections in Division I male collegiate soccer players. **Methods:** Twenty-three athletes completed two maximal-effort 20m sprints from a standing start position through an optical measurement system. Sprint characteristics measured included sprint velocity (SV), step length (SL), step frequency (SF), ground contact time (GCT), and flight time (FT). Each characteristic was recorded at approximately 2.5, 6, and 12m. Sprint characteristics at each distance were compared using a one-way repeated measures ANOVA. **Results:** The results indicated that SV, SL, SF, and FT were statistically greater at 12m in comparison to 6m ($p = 0.000$) and 2.5m ($p = 0.000$), while GCT was statistically shorter at 12m compared to 6m ($p = 0.000$) and 2.5m ($p = 0.000$). Additionally, sprint characteristics at 6m also displayed the same relationships when compared to 2.5m, with SV, SL, SF, and FT being statistically greater ($p = 0.000$) at this distance, and GCT being statistically shorter ($p = 0.000$) as well. **Conclusions:** Based on these differences, these results suggest that the acceleration phase may effectively be differentiated into early, mid, and late sub-sections within this athlete population. More precisely, these sub-sections appear to be congruent with distances of approximately 2.5, 6, and 12m, respectively.

Key Words: *speed development, field sport athletes, training specificity*

Introduction

Sprint acceleration is perhaps the most critical skill for field sport athletes (FSA) to attain. Due to the intermittent style of gameplay, these athletes are often prevented from reaching maximum sprint velocity during competition (20, 28, 34, 47). Instead, they are exposed to greater volumes of high-intensity sprints over short distances with frequent changes of direction (20, 28, 34). Based on this information, it should come as no surprise that higher-level FSA cover these short distances at greater speeds than their lower-level counterparts (10, 21, 23, 24). Despite the wide range of methods used to enhance sprint acceleration, typical modalities often include resistance training, resisted sprinting, plyometrics, and sprint drills (12, 14, 45). The majority of these tools aim to improve acceleration by utilizing the training principle of specificity (56).

More precisely, training methods such as resisted sprinting, plyometrics, and sprint drills are used to mimic sprint mechanics to foster a positive transfer of training effect. While there is research to support the efficacy of these modalities (12, 14, 31, 39, 45, 53, 55), task specificity may also be influenced by a number of important considerations including training volume and intensity. If these training variables are not appropriately managed, the training modality may not posses the same level of specificity, which may result in forfeiting a positive transfer of training effect. For example, multiple studies have investigated the optimal load for sled towing to improve sprint performance (9, 31, 35), as loads that are too light may not provide a sufficient overload, while excessive loads may compromise sprint technique. Other studies by Lockie et al. (39) and Spinks et al. (55) have investigated the effectiveness of resisted sprint training versus un-resisted sprint training. However, a critical detail, often overlooked, is the distance over which these training methods are performed. This is a crucial consideration in that acceleration

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mechanics are dynamic in nature. That is, the biomechanics inherent to the acceleration phase undergo a progressive sequence of changes prior to reaching maximum sprint velocity (42, 49-51).

This is likely reflected in sequential changes in key sprint metrics such as sprint velocity (SV), step length (SL), step frequency (SF), flight time (FT), ground contact time (GCT), and height of the center of gravity (COG) during the stance phase (4, 13, 40, 42, 51). It has even been suggested that the acceleration phase can be differentiated into multiple sub-sections based on these differences (4, 41, 42, 49-51). For example, Mann (42) has previously suggested that the acceleration phase can be divided into the "start" and the "transition" based on changes in an athlete's SV. In particular, Mann (42) has found sprinters to attain approximately 50% of their maximum velocity by the end of the start, which he characterized as steps 1-2. Additionally, sprinters also appear to attain approximately 80% of their top-end speed by the end of step 10, thus establishing the transition phase as steps 3-10 (42). In contrast to this framework, Nagahara et al. (49) identified early-, mid-, and late-acceleration based on the mean height of sprinters' COG during the stance phase. Interestingly, Nagahara and colleagues (49) found these acceleration zones to coincide with steps 1-3, 5-15, and 16-28, respectively. Mackala and colleagues (41), on the other hand, characterized these sub-phases based on specific sprint distances rather than steps. These investigators identified "starting acceleration", "main acceleration", and the "third transition", which is typically exclusive to elite sprint athletes, as 0-12, 12-35, and 35-60m, respectively. However, it is difficult to apply these concepts to field sport populations because this information was derived from track and field athletes beginning each sprint effort from starting blocks. Therefore, it has been suggested that further exploration of the

acceleration phase be carried out over distances that are more specific to FSA (e.g. – 5-15m) (1, 10).

Presently, a number of studies have investigated acceleration ability in FSA over these distances with respect to level of playing ability (10, 21, 23, 24, 29) and strength-related qualities (11, 43, 57, 59). Conversely, there is a paucity of research that has outlined the changes in sprint characteristics at these distances within a FSA population (4, 37, 38, 47). Most notably, a recent study by Barr and colleagues (4) examined key sprint characteristics (i.e. – SV, SL, SF, FT, and GCT) at a number of distances during 50m maximal-efforts in elite rugby players. The authors concluded that differences in these variables occurring at approximately 6, 12, and 18m suggest that these distances likely represent the early, mid, and late sub-phases of sprint acceleration. Although the results of Barr et al. (4) highlight the importance of acceleration ability up to 18m, the average sprint distances in other field sports, such as soccer, appear to be shorter (e.g. – 12-15m) (2). In fact, Vigne and colleagues (58) reported that approximately 75% of sprints performed by elite Italian soccer players were at distances of ≤9m over the course of a match. Other studies have also indicated that the first three steps of acceleration may also play a critical role in determining acceleration ability in the latter half of this phase of sprinting in FSA (37, 47). Due to these differences, the paradigm proposed by Barr et al. (58) cannot be assumed valid in a different population of FSA.

Therefore, further research needs to be conducted to clarify the distances that best characterize early-, mid-, and late-acceleration in other populations of FSA, particularly soccer players. Such information is critical for practitioners to facilitate greater training specificity, and, subsequently, a superior transfer of training effect. Consequently, the purpose of this study is to investigate the differences in sprint metrics occurring at distances of approximately

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2.5, 6, and 12m in a population of Division I men's soccer players. The investigators hypothesize that SV, SL, SF, and FT will increase as the athlete progresses from one acceleration zone to the next. In contrast, the investigators also hypothesize that ground GCT will show the opposite trend by displaying higher values during early-acceleration, and progressively shorter contacts as the athletes attain greater SV during mid- and late-acceleration.

METHODS

Experimental Approach to the Problem

A repeated measures design was used to compare SV, SL, SF, GCT, and FT at steps 3, 6, and 9 during 20m maximal-effort sprints. All participants completed each sprint trial within the same session. These measurements were made as a part of an on-going athlete monitoring program.

Participants

The athletes in this study included twenty-three Division I male collegiate soccer players (age = 20.7 ± 1.2 years, height = 179.38 ± 6.09cm, body mass = 76.4 ± 6.5kg). All athletes met the inclusion criteria of having at least one year of resistance training experience and two years of soccer experience. Additionally, each individual read and signed a written informed consent form prior to participating in any testing procedures. This study was approved by the East Tennessee State University Institutional Review Board.

Testing Procedures

Prior to sprint testing, each athlete underwent a standardized warm-up consisting of light jogging, brief dynamic stretches, and submaximal build-ups at 50% and 75% of perceived

maximum effort. Upon completion of the warm-up protocol, each athlete performed 3

maximum-effort 20m sprints with a 3-5 minute rest period between each trial. Each trial was

initiated from a standing start position 30cm behind the starting line (Figure 3.1). This 30cm

buffer was used to ensure the athletes' knees did not accidentally trigger the electronic timing

gates prior to initiating their start. Each standing start was performed with the athlete's preferred

leg forward, which they regularly performed during their dynamic warm-up prior to field

practices.

Figure 3.1 Starting position for the 20m-sprint test

Data Collection

20-meter sprint times were recorded using two electronic timing gates (Brower Timing

Systems, Draper, UT). Sprint characteristics were recorded using the OptoJump Next system

(Microgate, Bolzano, Italy). This optical measurement system is composed of transducer and receiver bars, which are each 1m in length. Each bar consists of 32 infrared light emitting bodies (LED) collecting at a sampling frequency of 1000 Hz. The average value of each sprint characteristic from the two fastest trials was used for analysis.

Sprint characteristics measured included SV, SL, SF, GCT, and FT for steps 3, 6, and 9, which were chosen to represent the distances of 2.5, 6, and 12m, respectively. These particular steps were chosen to represent their respective distances based on pilot data, as each of these steps was in closest proximity to their associated distance. For example, the footfall that was closest to 2.5m in nearly every 20m-sprint trial during pilot testing was step 3. The same relationship was also found between step 6 and 6m as well as step 9 and 12m. Accordingly, these steps appear to best represent acceleration zones 1, 2, and 3 for this athlete population. Although additional sub-sections of the acceleration phase may exist at further sprint distances (e.g. – 18m), these zones will be referred to as the "early-", "mid-", and "late-acceleration" zones for the purpose of this study, as these distances are based on those inherent to men's soccer players during competition. Furthermore, sprint characteristics at greater distances, such as the 18m-mark proposed by Barr et al. (4) in elite rugby athletes, are likely less relevant to this athlete population.

It is also important to note that the pilot data on which these methods were derived included the 30cm space between the athletes' lead foot and the starting line to ensure the athlete's knees or arms did not prematurely trigger the timing gates. Consequently, this 30cm buffer should not have altered the relationships between these steps and their associated distances. Also, the first timing gate was stationed at a lower position of 40cm, whereas the second was at a higher position of 110cm. The rationale for these positions was to ensure that the

athlete's hands did not prematurely trigger the timing gate prior to initiating their start.

Statistical Analysis

The test-retest reliability of measurements was assessed using intraclass correlation coefficients (ICC) and coefficients of variation (CV). 95% confidence intervals were also used to quantify the precision of measurement for all variables. A series of one-way repeated measures ANOVA were used to compare the differences in SV, SL, SF, and GCT between each acceleration zone. If the assumption of sphericity was violated, Greenhouse-Geiser adjusted values were used. When necessary, *post*-hoc analyses were performed using the Bonferroni correction technique. Cohen's *d* effect sizes were calculated and interpreted based on the scale proposed by Hopkins (30). Statistical power (*c*) was also calculated. All statistical analysis were calculated using SPSS version 21 (IBM, New York, NY) and statistical significance was set to *p* < 0.05 for all analyses.

RESULTS

Descriptive and test-retest reliability statistics are listed in Tables 3.1, 3.2, 3.3, 3.4, and 3.5 for SV, SL, SF, GCT, and FT, respectively. All sprint variables were found to be within an acceptable range of reliability with ICC values of 0.74 – 0.97 and CV values of 1.20 – 9.00%. Statistical differences in SV ($F_{2,21}$ = 778.64, *p* = 0.000, *c* = 1.000), SL ($F_{2,21}$ = 1260.75, *p* = 0.000, *c* = 1.000), SF ($F_{2,21}$ = 10.47, *p* = 0.000, *c* = 1.000), GCT ($F_{2,21}$ = 92.16, *p* = 0.000, *c* = 1.000), and FT ($F_{2,21}$ = 61.70, *p* = 0.000, *c* = 1.000) were found between acceleration zones 1, 2, and 3. Pairwise comparisons revealed that SV, SL, SF, and FT in acceleration zone 3 were statistically greater than acceleration zones 2 and 1 (Table 3.7). Additionally, SV, SL, SF, and FT at acceleration zone 2 were also statistically greater than zone 1 (Table 3.7). In contrast, GCT

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in acceleration zone 3 was statistically greater than acceleration zones 1 and 2. GCT in

acceleration zone 2 was also statistically shorter than zone 1 (Table 3.7).

Table 3.1 Descriptive statistics for sprint velocity during early, middle, and late acceleration

Acceleration Zones	Mean	SD	95% CI	ICC	CV (%)
Zone 1 – Step 3 (m/s)	5.54	0.25	5.44 – 5.67	0.74	3.35
Zone 2 – Step 6 (m/s)	7.01	0.27	6.90 – 7.13	0.83	2.11
Zone 3 – Step 9 (m/s)	8.02	0.27	7.91 – 8.15	0.84	1.77

Table 3.2 Descriptive statistics for step length during early, middle, and late acceleration

Acceleration Zones	Mean	SD	95% CI	ICC	CV (%)
Zone 1 – Step 3 (cm)	129.04	8.41	125.41 – 132.68	0.95	1.41
Zone 2 – Step 6 (cm)	157.80	9.85	153.55 – 162.06	0.96	1.50
Zone 3 – Step 9 (cm)	177.43	9.12	173.49 – 181.40	0.95	1.20

Table 3.3 Descriptive statistics for step frequency during early, middle, and late acceleration

Acceleration Zones	Mean	SD	95% CI	ICC	CV (%)
Zone 1 – Step 3 (steps/s)	4.31	0.31	4.18 – 4.45	0.86	3.54
Zone 2 – Step 6 (steps/s)	4.46	0.27	4.34 – 4.58	0.89	2.51
Zone 3 – Step 9 (steps/s)	4.53	0.23	4.44 – 4.68	0.86	2.36

Table 3.4 Descriptive statistics for ground contact time during early, middle, and late acceleration

Acceleration Zones	Mean	SD	95% CI	ICC	CV (%)
Zone 1 – Step 3 (ms)	157.02	14.13	150.91 – 163.14	0.94	2.70
Zone 2 – Step 6 (ms)	142.04	10.34	137.57 – 146.52	0.93	2.40
Zone 3 – Step 9 (ms)	132.26	9.41	128.19 – 136.33	0.95	2.02

Table 3.5 Descriptive statistics for flight time during early, middle, and late acceleration

Acceleration Zones	Mean	SD	95% CI	ICC	CV (%)
Zone 1 – Step 3 (ms)	64.28	11.97	59.39 – 69.17	0.91	9.00
Zone 2 – Step 6 (ms)	77.65	3.68	76.15 – 79.15	0.93	4.94
Zone 3 – Step 9 (ms)	87.52	3.99	85.89 – 89.15	0.88	4.60

Table 3.6 Effect sizes between acceleration zones for all sprint variables

Acceleration Zone	Cohen's *d*
SV Zone 1 versus Zone 2	5.65
SV Zone 2 versus Zone 3	3.74
SV Zone 1 versus Zone 3	9.53
SL Zone 1 versus Zone 2	3.14
SL Zone 2 versus Zone 3	2.07
SL Zone 1 versus Zone 3	5.52
SF Zone 1 versus Zone 2	0.52
SF Zone 2 versus Zone 3	0.28
SF Zone 1 versus Zone 3	0.81
GCT Zone 1 versus Zone 2	1.21
GCT Zone 2 versus Zone 3	0.99
GCT Zone 1 versus Zone 3	2.06
FT Zone 1 versus Zone 2	1.00
FT Zone 2 versus Zone 3	0.91
FT Zone 1 versus Zone 3	1.89

Table 3.7 Differences in sprint characteristics between acceleration zones.

Sprint Characteristic	Zone 1	Zone 2	Zone 3
Sprint Velocity (m/s)	5.54 ± 0.25	7.01 ± 0.27**	8.02 ± 0.27*
Stride Length (cm)	129.04 ± 8.41	157.80 ± 9.85**	177.43 ± 9.12*
Stride Frequency (m/s)	4.31 ± 0.31	4.46 ± 0.27**	4.53 ± 0.23*
Ground Contact Time (ms)	157.02 ± 14.13	142.04 ± 10.34 †	132.26 ± 9.41***
Flight Time (ms)	64.28 ± 11.97	77.65 ± 3.68**	87.52 ± 3.99*

* = Statistically greater than zones 1 and 2 ($p = 0.000$), ** = Statistically greater than zone 1

($p = 0.000$), *** = Statistically shorter than zones 1 and 2 ($p = 0.000$), † = Statistically

shorter than zone 1 ($p = 0.000$)

DISCUSSION

        The primary purpose of this study was to investigate the differences in sprint metrics occurring at distances of approximately 2.5, 6, and 12m in a population of Division I men's soccer players. The investigators hypothesized that SV, SL, SF, and FT would increase in accordance with greater sprint distances, while GCT would decline during mid- and late-acceleration. The main findings of this study support this hypothesis. Specifically, the late-acceleration zone displayed statistically greater SV, SL, SF, and FT, as well as statistically lower GCT, compared to the early- and mid-acceleration segments (Table 3.7). The mid-acceleration zone displayed the same relationships when compared to early-acceleration as well (Table 3.7). Cohen's *d* effect sizes indicated very large differences between each acceleration zone for SV and SL (Table 3.6). The effect sizes also indicated moderate to very large practical effects for FT and GCT between all phases of acceleration, and small-to-moderate effects for SF (Table 3.6).

        These results further support the notion that the acceleration phase can be differentiated into multiple sub-sections (4, 40, 42, 49-51). Furthermore, these findings also suggest that the early-, mid-, and late-acceleration zones may be defined as approximately 0-3, 3-6, and 6-12m, respectively, in a population of Division I collegiate men's soccer players. The results of this study, particularly with respect to the mid- and late- acceleration zones, are in accordance with those of Barr et al. (4). The results of Barr et al. (4) also suggest that greater distances, such as 18-20m, may also possess different sprint characteristics as the athlete approaches maximum velocity. Although the majority of sprints during a men's soccer match appear to be in accordance with those included in this study, practitioners are also encouraged to address sprint capabilities closer to top-end speed once the requisite skill of acceleration is attained.

The distances of the acceleration zones identified in the current study appear to be shorter than others suggested in previous literature (41, 42, 49, 50). This may be due to the fact that these investigations included athlete populations of trained sprinters who began each effort from starting blocks, whereas the athletes in the present study and Barr et al. (4) initiated each sprint from a standing start position. This may have had a significant impact on acceleration performance, as the use of starting blocks likely allowed the sprint athletes to achieve a steeper anterior lean of the torso following block clearance (36). However, common sense also suggests that populations of trained sprinters likely possess greater top-end speed than FSA. This is evident when considering the fact that every rugby athlete in Barr et al. (4) achieved maximum velocity between 33-39m, whereas elite sprinters have been shown to attain maximum velocity between 50-70m (7, 25).

This discrepancy may also be related to the intermittent demands of field sports. Specifically, FSA are often walking, jogging, running, or changing direction when they begin to accelerate during gameplay (3). Accordingly, these athletes are likely more experienced in re-accelerating while "on the move" rather than accelerating from a static position. The rationale for using a staggered start position in this study was twofold. First, using a static start position allowed each trial to be standardized for every athlete. Secondly, the goal of this investigation was to identify appropriate acceleration distances for speed development practices in collegiate male soccer players. The common methods of developing acceleration previously discussed (i.e. – resisted sprints and various sprint drills) are typically performed from a static position. While some may argue that these practices lack sport specificity, there is evidence indicating that these tactics likely transfer to sport. For example, multiple studies have concluded that higher-level soccer players display faster sprint speeds than their lower-level counterparts during 10-30m

sprint tests (10, 21, 26). While these results provide practical value, a detail that is often overlooked is that all the sprint tests employed in these studies were performed from a static starting position. Based on this information, it can be surmised that improvements in sprint acceleration from a static position will likely transfer to sport, as faster athletes are most often those playing at a higher level.

With respect to the training process, these results may be useful in creating an integrated methodology for strength, power, and speed development for FSA. Such an approach was developed by DeWeese and colleagues (17, 18) for track and field and bobsled athletes, which was coined Seamless Sequential Integration (SSI). This model merged the tenants of block periodization (BP), conjugate sequential sequencing (CSS), and a short-to-long approach (S2L) to speed development into a unified framework (17, 18). In short, this methodology aimed to augment an athlete's acceleration capabilities early in the training year, while maximizing strength-related qualities such as strength endurance (SE) and maximal strength (MS). As these fitness qualities matured, the focus of training shifted towards maximizing rate of force development (RFD), which served to compliment sprint speeds that approached maximum velocity (5, 17-19). However, due to the shorter distances covered in soccer, it may be more appropriate to develop each sub-section of acceleration in conjunction with SE, MS, and RFD, rather than the entire acceleration and maximum velocity phases.

From a speed development perspective, dedicating more time to address each sub-phase of acceleration, rather than developing the entire phase as a whole, may facilitate performance improvements that are more specific to soccer. When combined with BP and CSS, a S2L for FSA may also elicit similar physiological responses as those believed to be developed in the traditional model, which may yield comparable performance adaptations. For example,

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supplying "concentrated loads" of activities to emphasize the development of early-acceleration and SE during the general preparatory phase of training may allow the athlete to enhance both of these qualities, as the higher resistance training volumes will likely be off-set with shorter sprint distances. From a physiological standpoint, this may limit the interference effect by maximizing the up-regulation of the mTOR pathway, while mitigating excessive phosphorylation of AMPk (48). The resulting increase in contractile protein synthesis will likely increase muscle cross-sectional area (46, 61), potentially bolstering the MS levels required to enhance the mid-acceleration zone in subsequent training phases (56). As Stone and colleagues remind us (56), MS can be seen as "the vehicle" driving a host of other adaptations, particularly the development of higher RFD. Subsequently, sequencing the training process to maximize this critical quality will likely have a positive impact on an athlete's ability to produce a high RFD, which is critical to attaining higher SV at greater distances, such as those inherent to late-acceleration and beyond (60).

An additional consideration to be noted is that the acceleration zones identified in this study were intended to serve as guidelines for practitioners and athletes. Since previous literature has suggested that sprint characteristics are, to a certain extent, relative to the individual (50, 52), one would expect these distances to differ slightly from one athlete to the next. However, these guidelines may be very useful when working with large groups, such as in a collegiate setting, where individual prescriptions are often impractical. Furthermore, these sub-sections of acceleration should not be used to rigidly develop each individual segment. Rather, they should be employed as a means to provide a particular emphasis in the athlete's training. For example, methods implemented to augment early-acceleration do not have to be performed exclusively at a distance of 2.5m. Rather, coaches and athletes are encouraged to select methods that aim to

improve the start, particularly the first three steps of acceleration, when addressing this segment. Moreover, these methods may include sprints at shorter distances of 5-15m, with the majority of these efforts residing in the 0-5 and 5-10m ranges. As previously stated, keeping these distances on the shorter end of this range may limit unnecessary training volume and, subsequently, fatigue. This may allow for better fatigue management and superior adaptations to take place (56).

In later training phases, however, the resistance training focus often shifts towards enhancing MS and RFD, as per the BP paradigm (15, 16, 56). When these transitions occur, the resistance training volume is typically lowered to accommodate for higher training intensities (6, 56). Accordingly, practitioners are encouraged to focus on longer distance accelerations that are in accordance with the mid- and late-zones, respectively, at these times of the training year. This is not to say that FSA should avoid accelerating beyond these distances. Quite the contrary, occasionally attaining maximum sprint velocity during training may offer neurological adaptations that are beneficial to acceleration (54). With that said, one cannot overlook the fact that high-level athletes are competing in substantially more events per year compared to previous decades (32). Due to more rigorous competitive schedules, training time has inherently diminished (32). Consequently, appropriately allocating training time to cultivate the most relevant skills to the sport is a logical tactic in addressing this issue as well as appropriately managing fatigue to enhance sprint performance.

Selecting the most appropriate training methods to enhance these skills is also a critical consideration to maximize training efficiency. Keeping this in mind, the results of the current study can also be used to assess the utility of particular speed development tactics, as the methods employed to emphasize a particular acceleration zone should possess similar sprint

metrics. In addition, one most also consider the impact that resistance training and sport practice may have on the athlete's performance capabilities as well. Using the SSI for FSA described above as an example, if the early-acceleration zone is coupled with establishing a foundation of SE during resistance training, the athlete may be fatigued from the high-workloads necessary to attain an enhanced work capacity. As a previous studies have indicated, greater levels of accumulated fatigue will likely suppress an athlete's RFD (22, 44), which could impact their ability to generate high ground reaction forces, thus limiting SV (60). Based on this information, methods that display inherently longer contact times, such as sled towing, incline sprinting, or select plyometric exercises, may be more effective in this situation. While this may sound counterintuitive, one may hypothesize that these tactics may require the athlete to generate a higher propulsive impulse (IP) over a longer period of time (27), thus accommodating for the diminished RFD. In combination with an understanding of training theory, the results of the current study can be used to identify the most appropriate training methods across a spectrum of scenarios.

Although kinetic variables such a RFD, IP, and peak power (PP) were not part of this investigation, the findings of this study may provide a heading for future investigations with respect to these variables during sprint acceleration. More specifically, human movement is influenced by both kinetic and kinematic parameters (33), so, disparities in movement patterns, such as differences in sprint characteristics, are likely accompanied by varying force-outputs (8). Therefore, future studies should aim to elucidate the differences in kinetic parameters that likely accommodate the changes in sprint metrics during acceleration. Such information may offer practical value to coaches by identifying particular training tasks (e.g. – resistance training

exercises, speed development methods, etc.) that are specific to a particular acceleration zone, potentially enhancing the transfer of training effect.

PRACTICAL APPLICATIONS

The findings of this study may assist practitioners in properly implementing speed development tactics for the purpose of improving sprint acceleration in male collegiate soccer players. While the precise distance constituting each phase of acceleration likely differs from one athlete to the next, accommodating to the precise needs of each individual athlete is often impractical in the collegiate setting. As such, distances of 2.5, 6, and 12m may be used as guidelines to emphasize the development of early-, mid-, and late-acceleration, respectively. Furthermore, these sub-sections can also be used to merge speed enhancement strategies with resistance training programs through the use of BP and CSS. The integration of these training components may aid practitioners in maximizing key performance characteristics at desired times of the training year.

References

1.   Bangsbo J, Norregaard L, and Thorso F. Activity profile of competition soccer. *Can J Sport Sci* 16: 110-116, 1991.
2.   Bangsbo J, Norregaard L, and Thorso F. Activity profile of competition soccer. *Can J Sport Sci* 16: 110-116, 1991.
3.   Barr M. A series of studies examining the development of sprint speed and momentum of international rugby union players, in: *School of Exercise and Health Sciences*. Edith Cowan University, 2014.
4.   Barr MJ, Sheppard JM, and Newton RU. Sprinting kinematics of elite rugby players. *Journal of austrailian strength and conditioning* 21: 14-20, 2013.
5.   Bellon CR. The relationship between strength, power, and sprint acceleration in field sport athletes in: *Exercise and Sport Science*. East Tennessee State University, 2016.
6.   Bompa T, Haff, G. . *Periodization: Theory and Methodology of Training*. Champaign, IL: Human Kinetics, 2009.
7.   Bruggerman GP and Glad B. Time analysis of the sprint events, in: *IAAF Scientific Research Project at the Games of the XXXIV Olympiad-Seoul 1998: Final Report*. GP Bruggemann, B Glad, eds. Italy, 1990, pp 10-45.
8.   Cappadona J. Kinematic and spatiotemporal analysis between sprint drills and maximal sprinting, in: *Physical Therapy & Human Movement Science*. Fairfield University: Sacred Heart University, 2013, p 52.
9.   Clark KP, Stearne DJ, Walts CT, and Miller AD. The longitudinal effects of resisted sprint training using weighted sleds vs. weighted vests. *J Strength Cond Res* 24: 3287-3295, 2010.
10.   Cometti G, Maffiuletti NA, Pousson M, Chatard JC, and Maffulli N. Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int J Sports Med* 22: 45-51, 2001.
11.   Comfort P, Bullock N, and Pearson SJ. A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *J Strength Cond Res* 26: 937-940, 2012.
12.   Cronin J, Hansen, K. Resisted sprint training for the acceleration phase of sprinting. *Strength & conditioning Journal* 28, 2006.
13.   Debaere S, Delecluse C, Aerenhouts D, Hagman F, and Jonkers I. From block clearance to sprint running: characteristics underlying an effective transition. *J Sports Sci* 31: 137-149, 2013.
14.   Delecluse C. Influence of strength training on sprint running performance. Current findings and implications for training. *Sports Med* 24: 147-156, 1997.
15.   DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part 2: Practical and applied aspects. *Journal of sport and health science* 4: 318-324, 2015.
16.   DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part I: Theoretical aspects. *Journal of sport and health science* 4: 308-317, 2015.
17.   DeWeese BH, Sams ML, and Serrano AJ. Sliding toward Sochi–part1: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach* 1: 30-42, 2014.

18.   DeWeese BH, Sams ML, and Serrano AJ. Sliding towards Sochi–part II: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach* 1: 4-7, 2014.

19.   DeWeese BH, Sams ML, Williams JH, and Bellon CR. The nature of speed: Enhancing sprint abilities through a short to long training approach, in: *Techniques in Track & Field and Cross Country*. 2015, pp 8-24.

20.   Duthie GM, Pyne DB, Marsh DJ, and Hooper SL. Sprint patterns in rugby union players during competition. *J Strength Cond Res* 20: 208-214, 2006.

21.   Ferro A, Villacieros J, Floria P, and Graupera JL. Analysis of speed performance in soccer by a playing position and a sports level using a laser system. *J Hum Kinet* 44: 143-153, 2014.

22.   Flanagan SD, Dunn-Lewis C, Comstock BA, Maresh CM, Volek JS, Denegar CR, and Kraemer WJ. Cortical Activity during a Highly-Trained Resistance Exercise Movement Emphasizing Force, Power or Volume. *Brain sciences* 2: 649-666, 2012.

23.   Gabbett T, Kelly J, Ralph S, and Driscoll D. Physiological and anthropometric characteristics of junior elite and sub-elite rugby league players, with special reference to starters and non-starters. *Journal of science and medicine in sport* 12: 215-222, 2009.

24.   Gabbett TJ, Kelly JN, and Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. *J Strength Cond Res* 22: 174-181, 2008.

25.   Gajer B, Thepaut-Mathieu C, and Lehenaff D. Evoluation of stride and amplitude during course of the 100m event in athletics. *New studies in athletics* 14: 43-50, 1999.

26.   Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, and Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Res Sports Med* 14: 205-214, 2006.

27.   Gottschall JS and Kram R. Ground reaction forces during downhill and uphill running. *J Biomech* 38: 445-452, 2005.

28.   Gregson W, Drust B, Atkinson G, and Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. *Int J Sports Med* 31: 237-242, 2010.

29.   Hoffman JR, Vazquez J, Pichardo N, and Tenenbaum G. Anthropometric and performance comparisons in professional baseball players. *J Strength Cond Res* 23: 2173-2178, 2009.

30.   http://sportsci.org/resource/stats/effectmag.html. Accessed January/2015.

31.   Hrysomallis C. The effectiveness of resisted movement training on sprinting and jumping performance. *J Strength Cond Res* 26: 299-306, 2012.

32.   Issurin V. Block periodization versus traditional training theory: a review. *J Sports Med Phys Fitness* 48: 65-75, 2008.

33.   Jaric S, Ristanovic D, and Corcos DM. The relationship between muscle kinetic parameters and kinematic variables in a complex movement. *Eur J Appl Physiol Occup Physiol* 59: 370-376, 1989.

34.   Jovanovic M, Sporis G, Omrcen D, and Fiorentini F. Effects of speed, agility, quickness training method on power performance in elite soccer players. *J Strength Cond Res* 25: 1285-1292, 2011.

35.   Kawamori N, Newton RU, Hori N, and Nosaka K. Effects of weighted sled towing with heavy versus light load on sprint acceleration ability. *J Strength Cond Res* 28: 2738-2745, 2014.

36. Kugler F and Janshen L. Body position determines propulsive forces in accelerated running. *J Biomech* 43: 343-348, 2010.

37. Lockie RG, Murphy AJ, Knight TJ, and Janse de Jonge XA. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res* 25: 2704-2714, 2011.

38. Lockie RG, Murphy AJ, Schultz AB, Jeffriess MD, and Callaghan SJ. Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *J Strength Cond Res* 27: 2494-2503, 2013.

39. Lockie RG, Murphy AJ, Schultz AB, Knight TJ, and Janse de Jonge XA. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res* 26: 1539-1550, 2012.

40. Mackala K. Optimisation of performance through kinematic analysis of the different phases of the 100 metres. *New studies in athletics* 22: 7-16, 2007.

41. Mackala K, Fostiak M, and Kowalski K. Selected determinants of acceleration in the 100m sprint. *J Hum Kinet* 45: 135-148, 2015.

42. Mann RV. *The mechanics of sprinting and hurdling.* Charlestown, SC, 2013.

43. Marques MC, Gil H, Ramos RJ, Costa AM, and Marinho DA. Relationships between vertical jump strength metrics and 5 meters sprint time. *J Hum Kinet* 29: 115-122, 2011.

44. Marshall PW, McEwen M, and Robbins DW. Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males. *Eur J Appl Physiol* 111: 3007-3016, 2011.

45. Martinez-Valencia MA, Romero-Arenas S, Elvira JL, Gonzalez-Rave JM, Navarro-Valdivielso F, and Alcaraz PE. Effects of Sled Towing on Peak Force, the Rate of Force Development and Sprint Performance During the Acceleration Phase. *J Hum Kinet* 46: 139-148, 2015.

46. Minetti AE. On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *Eur J Appl Physiol* 86: 363-369, 2002.

47. Murphy AJ, Lockie RG, and Coutts AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sports Sci Med* 2: 144-150, 2003.

48. Nader GA. Concurrent strength and endurance training: from molecules to man. *Med Sci Sports Exerc* 38: 1965-1970, 2006.

49. Nagahara R, Matsubayashi T, Matsuo A, and Zushi K. Kinematics of transition during human accelerated sprinting. *Biol Open* 3: 689-699, 2014.

50. Nagahara R, Naito H, Morin JB, and Zushi K. Association of acceleration with spatiotemporal variables in maximal sprinting. *Int J Sports Med* 35: 755-761, 2014.

51. Rabita G, Dorel S, Slawinski J, Saez-de-Villarreal E, Couturier A, Samozino P, and Morin JB. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scandinavian journal of medicine & science in sports* 25: 583-594, 2015.

52. Rahmani A, Locatelli E, and Lacour JR. Differences in morphology and force/velocity relationship between Senegalese and Italian sprinters. *Eur J Appl Physiol* 91: 399-405, 2004.

53. Rimmer E and Sleivert G. Effects of a plyometrics intervention program on sprint performance. *Journal of strength and conditioning research* 14: 295-301, 2000.

54. Ross A, Leveritt M, and Riek S. Neural influences on sprint running: training adaptations and acute responses. *Sports Med* 31: 409-425, 2001.

55. Spinks CD, Murphy AJ, Spinks WL, and Lockie RG. The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and Australian football players. *J Strength Cond Res* 21: 77-85, 2007.
56. Stone MH, Stone, M., Sands, W. A. *Principles and Practice of Strength Training.* Champaign, IL: Human Kinetics, 2007.
57. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between isometric mid-thigh pull variables and sprint change of direction in collegiate athletes. *Journal of trainology* 4: 6-10, 2015.
58. Vigne G, Gaudino C, Rogowski I, Alloatti G, and Hautier C. Activity profile in elite Italian soccer team. *Int J Sports Med* 31: 304-310, 2010.
59. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, La Monica MB, Beyer KS, Church DD, Fukuda DH, and Jeffrey SR. Isometric Mid-Thigh Pull Correlates with Strength, Sprint and Agility Performance in Collegiate Rugby Union Players. *J Strength Cond Res*, 2016.
60. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950-961, 2010.
61. Zamparo P, Minetti AE, and di Prampero PE. Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: theory and facts. *Eur J Appl Physiol* 88: 193-202, 2002.

CHAPTER 4

THE RELATIONSHIP BETWEEN STRENGTH-RELATED VARIABLES AND SPRINT
CHARACTERISTICS IN DIVISION I MEN'S SOCCER PLAYERS

Authors: [1]Christopher R. Bellon, [1]Brad H. DeWeese, [1]Kimitake Sato, [2]Kenneth P. Clark,
[1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of

Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Kinesiology, West Chester University, West Chester, PA, USA

Abstract

Purpose: The purpose of this study was to investigate the relationships between various strength-power variables and key sprint characteristics within the early, mid, and late sub-phases of sprint acceleration in Division I men's soccer players. **Methods:** Twenty-one athletes performed static jumps (SJ) and countermovement jumps (CMJ) with loads of 0 and 20kg on dual force platforms. Allometrically scaled peak power (PPa) and peak power relative to body mass (PPr) were measured with every load for each jump condition. Isometric mid-thigh pulls (IMTP) were also performed on dual force platforms. Allometrically scaled peak force (IPFa) and isometric rate of force development (IRFD) were measured at time points of 90 (IRFD@90), 200 (IRFD@200), and 250 (IRFD@250) milliseconds. Lastly, 20m sprints were performed through an optical measurement system, which recorded sprint velocity (SV), step length (SL), step frequency (SF), and ground contact time (GCT) within each zone. Pearson product-moment correlations (r) were calculated to examine the relationships between SJ, CMJ, IMTP, and sprint variables. **Results:** IRFD@90 displayed moderate-to-strong, negative correlations with GCT ($r = -.337 - -.541$) and small-to-moderate, positive correlations with SF ($r = .270 - .430$) within each acceleration zone. SJ PPr at 0kg also showed moderate-to-strong, negative correlations with GCT ($r = -.439 - -.511$) and moderate-to-strong, positive correlations with SF ($r = .293 - .490$) within each acceleration zone. **Conclusions:** It appears that IRFD@90 and SJ PP at 0kg may be related to shorter GCT and greater SF during sprint acceleration in Division I men's soccer players.

Key Words: *rate of force development, peak power, speed development*

Introduction

The nature of team sports is inherently chaotic. Gameplay often consists of short sprints across an array of distances with frequent changes of direction (20, 23, 33, 45). Due to the disorderly nature of these sports, field sport athletes (FSA) seldom reach maximum sprint velocity during competition, thus making sprint acceleration a vital skill for these athlete populations (15, 45). Perhaps even more important, sprint acceleration has been shown to occur most often at key points during competition, such as creating a scoring opportunity or dodging a defender (21, 42, 50). Although team sports often revolve around skills such as dribbling, passing, and shooting, the ability to express these attributes is likely influenced by an athlete's facility to accelerate.

One of the primary tools employed to improve sprint acceleration is resistance training (17). This is not surprising considering that a wealth of studies and reviews have shown strength-power measures such as maximal strength (MS) (1, 12, 16, 41, 52), rate of force development (RFD) (22, 54, 62, 64, 65), and peak power (PP) (1, 15, 16, 54) are positively related to superior acceleration ability. Other means of improving acceleration performance include resisted sprinting (14), plyometrics (39), and sprint drills (8, 35). These methods are often implemented to mimic the spatiotemporal characteristics of sprinting, in hopes of fostering a positive transfer of training effect. This is also a logical training approach because in addition to delivering higher ground reaction forces (GRF) with greater efficiency, faster FSA also appear to display different sprint characteristics during the acceleration phase as well (28, 37, 45). Despite these kinematic differences between "fast" and "slow" FSA, the dynamic nature of sprint mechanics during acceleration appears to be universal in this athletic population. In other words, as an athlete attains greater sprint velocity (SV), the change in sprint speed is accompanied by sequential

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changes in key sprint characteristics such as step length (SL), step frequency (SF), and ground

contact time (GCT) (3, 5).

From a speed development perspective, these changes are important to note, as it has

recently been suggested that the alterations in sprint metrics can be used to divide the

acceleration phase into constituent sub-sections in FSA (3, 5). Furthermore, these spatiotemporal

alterations can be used to demarcate an "early-", "mid-", and "late-" phase of sprint acceleration.

This concept was illustrated in a recent study by Barr et al. (3), who characterized the

acceleration patterns of elite rugby players during a 50-meter maximal effort. Based on the

differences in a variety of sprint metrics including sprint velocity (SV), SL, SF, flight time (FT),

and GCT, Barr and colleagues (3) concluded that the early-, mid-, and late-acceleration zones for

elite rugby players may be characterized as 0–6, 6–12, and 12–18m, respectively. Surprisingly,

the authors did not differentiate the initial three steps into a separate sub-section. This is likely an

important consideration because these contacts have been shown to influence acceleration ability

at greater distances (37, 45).

However, this initial sub-section was included in a similar study by Bellon (5), who also

examined the same sprint metrics as Barr et al. (3), but over distances of approximately 2.5, 6,

and 12m. In contrast to Barr et al. (3), the investigation by Bellon (5) included a population of

Division I men's collegiate soccer players. Accordingly, the distances selected for that study

were inherently shorter than those used by Barr and colleagues (3), as the average sprint distance

during a soccer match likely resides between 9–12m (2, 63). The results reported by Bellon (5)

revealed statistically significant differences in each sprint characteristic occurring at each

distance. Specifically, the late-acceleration zone (6–12m) displayed statistically greater SV ($p =$

0.000), SL ($p = 0.000$), SF ($p = 0.000$), and FT ($p = 0.000$) and statistically shorter GCT ($p =$

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0.000) compared to the mid- (2.5–6m) and early-acceleration (0–2.5m) sub-phases. Additionally, the mid-acceleration zone displayed the same relationships in comparison to early-acceleration as well. While Bellon (5) illustrated the kinematic differences that likely separate the sub-phases of acceleration in collegiate men's soccer players, the underlying strength-power variables that govern each segment remain unknown.

This is important because, as Siff (53) reminds us, a positive transfer of training effect depends not only on the mechanical specificity of a task, but also the kinetic specificity as well. When viewed from this perspective, the kinetic parameters of a training task, such as the magnitude of force applied, RFD, and PP, are of equal importance in successfully transferring training adaptations to athletic performance. Accordingly, understanding which of these kinetic variables are most relevant to each sub-section of acceleration is crucial to selecting appropriate exercises to develop this skill. However, no studies have been conducted to identify which of these measures are most relevant to the sub-phases of acceleration. Consequently, the primary purpose of this study is to investigate the relationship between various strength-power variables and key sprint characteristics within the early-, mid-, and late-acceleration zones in a population of Division I men's soccer players. The investigators hypothesize that the strongest relationships will be found between RFD, PP, and GCT. More specifically, the investigators believe that RFD at later time points (e.g. – 200 and 250ms) will display the strongest correlations with GCT during early-acceleration, when contact time is likely longer. In contrast, the authors further hypothesize that RFD at earlier time windows (e.g. – 90ms) will show stronger relationships with GCT during late-acceleration, which is likely to display longer foot contacts.

METHODS

Experimental Approach to the Problem

Athletes completed static jumps (SJ), countermovement jumps (CMJ), isometric mid-thigh pulls (IMTP), and 20m maximal-effort sprints over a single testing session. Pearson product-moment correlations were used to compare the relationships between sprint characteristics at steps 3, 6, and 9 during the 20m sprints and various strength-power variables from the SJ, CMJ, and IMTP. Specifically, allometrically scaled PP (PPa) and PP relative to body mass (PPr) at loads of 0 and 20kg were collected for each jump test, as both SJ (15) and CMJ (1) have been positively correlated with acceleration performance. Additionally, IPFa and isometric RFD (IRFD) at time windows of 90ms (IRFD@90), 200ms (IRFD@200), and 250ms (IRFD@250) were collected during IMTP testing. IPFa was collected to represent the athletes' relative strength levels, which has also been related to acceleration performance (11). Lastly, IRFD measures were collected at time points of 90, 200, and 250ms to evaluate the importance of the "force" and "velocity" ends of the force-velocity curve during each sub-phase of acceleration, as a wide variety of sport movements appear to occur within this range (24, 61). Each of these measurements was made as a part of an on-going athlete monitoring program.

Participants

The athletes in this study included twenty-one Division I male collegiate soccer players (age = 20.7 ± 1.2 years, height = 179.38 ± 6.09cm, 76.4 ± 6.5kg). All athletes met the inclusion criteria of having at least one year of resistance training experience and two years of soccer experience. Additionally, each individual read and signed a written informed consent form prior to participating in any testing procedures. This study was approved by the East Tennessee State University Institutional Review Board.

Testing Procedures

Warm-Up

Prior to performing any strength, power, or speed testing, each athlete participated in a standardized warm-up protocol. This procedure included 25 jumping jacks and a series of mid-thigh clean pulls with a standard 20kg barbell (Werksan, Turkey). Specifically, the mid-thigh clean pulls were performed for 1 set of 5 repetitions and 3 sets of 5 repetitions with loads of 20kg and 60kg, respectively.

Static and Countermovement Jump Testing

Following the completion of the standardized warm-up, each athlete participated in vertical jump testing consisting of static jumps (SJ) and countermovement jumps (CMJ). Each condition was performed using loads of 0kg (PVC pipe) and 20kg (barbell). The athletes performed each jump by holding the 0kg or 20kg implement just below the seventh cervical vertebra (9, 58). Each maximum effort jump trial was performed on 91.4x91.4cm dual force platforms (Rice Lake Weighing Systems, Rice Lake, WI) with sampling rates of 1000 Hz. SJ were performed prior to CMJ, as the order in which jump conditions are completed does not seem to positively or negatively affect performance (34). In preparation for the SJ, each athlete was instructed to firmly grasp the 0kg or 20kg bar and assume a squat position with a 90° knee angle, which was measured using a handheld goniometer (Figure 1). Once this position was acquired, the athletes completed practice jumps at 50% and 75% of perceived maximum effort. It is important to note that the athletes were instructed to be still when holding the "ready position" to eliminate any use of the stretch-shortening cycle (SSC) (25). For the maximum effort SJ trials, the athletes were instructed to firmly hold the 0kg or 20kg bar, step onto the force platforms, and assume the "ready position". Upon acquiring the proper position, a countdown of "3-2-1 Jump"

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was given. The average of two trials within 2cm was used for analysis for each load. Additional trials were performed if the athlete appeared to put forth less than a maximum effort, used a SSC, or if the difference in jump height between attempts was greater than 2cm. A rest period of 1-minute was provided between jump trials. A minimum of two trials was completed at both 0kg and 20kg, with 0kg jumps being performed first. Upon the completion of all SJ trials, a 3-minute rest period was given prior to performing CMJ.

The same procedures were applied to CMJ testing. However, unlike the SJ, the athletes executed these jumps without a pause to a self-selected depth, as described by Kraska et al. (36). Prior to each trial, the participant was instructed to firmly grasp the 0kg or 20kg bar, step onto the force platforms, stand in an upright position, and await the countdown of "3, 2, 1 Jump". The average of two trials within 2cm was used for analysis for each load. Additional trials were performed if the athlete appeared to put forth less than a maximum effort or if the difference in jump height between attempts was greater than 2cm.

SJ and CMJ force-time data obtained from the force plates were filtered using a digital low-pass Butterworth filter with a cutoff frequency of 10 Hz and analyzed using a custom-built Labview program (LabView 8.5.1, 8.6, and 2010, National Instruments Co., Austin, TX). Peak power (PP) was calculated from the power-time data from each force plate. Allometrically scaled peak power (PPa) was calculated using the allometric scaling expression: Absolute PP (W)/(Body Mass (kg)$^{.67}$). Relative peak power (PPr) was calculated by simply dividing PP by the athlete's body mass.

Figure 4.1 Static jump "ready position"

Isometric Mid-Thigh Pull Testing

Following the completion of vertical jump testing, the athletes were positioned inside a

power rack and guided into the appropriate joint angles to properly perform the IMTP test.

Although body angles varied from one individual to the next due to anthropometrical differences,

each athlete achieved knee and hip angles between 125-135 and 145-155 degrees, respectively

(4) (Figure 2). Each pulling trial was performed while standing on 91.4x91.4cm dual force

platforms (Rice Lake Weighing Systems, Rice Lake, WI) with sampling rates of 1000 Hz. These

platforms were positioned inside a custom-built power rack that allowed the bar to be adjusted to

any height. Once the permissible body positions were achieved, the athletes were given lifting

straps and performed 2 practice repetitions at 50% and 75% of perceived maximal effort. Prior to

performing the first trial at maximal intensity, the athlete's hands were secured to the bar using

athletic tape. Finally, the athlete was placed back into the proper pulling position and awaited the

tester's countdown of "3, 2, 1 Pull". The testers gave verbal encouragement for the duration of every maximal effort attempt. The attempts were terminated when the athlete displayed a plateau or a steady decrease in force output. Following each pull, the athletes were given a minimum rest period of 3-minutes.

Isometric mid-thigh pull (IMTP) force-time data obtained from the force plates were filtered using a digital low-pass Butterworth filter with a cutoff frequency of 10 Hz and analyzed using a custom-built Labview program (LabView 8.5.1, 8.6, and 2010, National Instruments Co., Austin, TX). The testing variables collected included allometrically scaled isometric peak force (IPFa), isometric rate of force development (IRFD) at 90ms ($IRFD_{90}$), IRFD at 200ms ($IRFD_{200}$), and IRFD at 250ms ($IRFD_{250}$). IPFa was calculated using the following allometric expression: Peak Force/(Body Mass $(kg)^{.67}$) (59).

Figure 4.2 Isometric mid-thigh pull position

20-Meter Sprints

Following IMTP testing, the athletes underwent an additional standardized warm-up consisting of light jogging, brief dynamic stretches, and submaximal build-ups at 50% and 75% of perceived maximum effort. Upon completion of the warm-up protocol, each athlete performed 3 maximum-effort 20m sprints with a 3-5 minute rest period between each trial. Each trial was initiated from a staggered start position 30cm behind the starting line (Figure 3). This 30cm buffer was used to ensure the athletes' knees did not prematurely trigger the electronic timing gates. 20m sprint times were recorded using electronic timing gates (Brower Timing Systems, Draper, UT). The first timing gate was stationed at a lower position of 40cm, whereas the second was at a higher position of 110cm. The rationale for these positions was to ensure that the athlete's hands did not prematurely trigger the timing gate prior to initiating their start. Sprint characteristics were recorded using the OptoJump Next system (Microgate, Bolzano, Italy). This optical measurement system is composed of transducer and receiver bars, which are each 1m in length. Each bar consists of 32 infrared light emitting bodies (LED) collecting at a sampling frequency of 1000 Hz. Sprint characteristics measured included SV, SL, SF, and GCT for steps 3, 6, and 9, which were chosen to represent the early- (0-2.5m), mid-, (2.5-6m) and late-acceleration (6-12m) zones, respectively. These steps were selected to represent their associated sub-sections based on the results of Bellon (5). The average value of each sprint characteristic from the two fastest trials was used for analysis.

Figure 4.3 Starting position for the 20m-sprint test

Statistical Analysis

The test-retest reliability of measurements was assessed using intraclass correlation coefficients (ICC), coefficients of variation (CV), and paired t-tests. 95% confidence intervals were also used to quantify the precision of measurement for all variables. The relationships between all jump, IMTP, and sprint variables within each acceleration zone were assessed using Pearson-product moment correlation coefficients. The strength of these relationships were evaluated based on the scale established by Hopkins (29). All statistical analysis were calculated using SPSS version 21 (IBM, New York, NY) and statistical significance was set to $p < 0.05$ for all analyses.

RESULTS

Descriptive and test-retest reliability data from jump and IMTP testing are displayed in Table 2.1. All jump variables showed acceptable reliability with ICC and CV values ranging from 0.80 – 0.97 and 2.28 – 5.05%, respectively. The IMTP variables also showed acceptable ICC values ranging from 0.86 – 0.98. However, while IPFa showed an acceptable CV at 2.54%, the CV values for each of the IRFD variables were less reliable, ranging from 18.33-36.67%. Despite finding higher CV values for these variables, paired t-tests did not show statistically significant differences between trials for IRFD@90 ($p = 0.49$), IRFD@200 ($p = 0.91$), IRFD@250 ($p = 0.92$). All sprint variables showed acceptable reliability with ICC values between 0.78 – 0.97 and CV values of 0.49 – 3.54%.

Pearson product-moment correlations displaying the relationships between jump, IMTP, and sprint characteristics during early-, mid-, and late-acceleration can be found in Tables 2.3, 2.4, and 2.5, respectively. GCT displayed statistically significant correlations with SJ PPr 0kg ($r = -0.493$, p $= 0.023$), IRFD90 ($r = -0.542$, $p = 0.011$), and IRFD200 ($r = -0.486$, $p = 0.025$) during early acceleration. During the mid-acceleration phase, SV showed statistically significant correlations with SJ PPa 0kg ($r = 0.549$, $p = 0.010$) and SJ PPr 0kg ($r = 0.543$, $p = 0.011$). Additionally, SJ PPr 0kg showed statistically significant correlations with GCT ($r = -0.447$, $p = 0.042$) and SF ($r = 0.490$, $p = 0.024$) within this phase of acceleration as well. SF also showed statistically significant correlations with IRFD200 ($r = 0.528$, $p = 0.014$) and IRFD250 ($r = 0.562$, $p = 0.008$). During the late acceleration phase, GCT showed statistically significant correlations with SJ PPr 0kg ($r = -0.511$, $p = 0.018$) and IRFD90 ($r = -0.444$, $p = 0.044$). SF displayed statistically significant correlations with IPFa ($r = 0.489$, $p = 0.025$) during the late

acceleration period as well. Although not statistically significant, 20m-time displayed moderate, negative correlations with SJ PPa 0kg ($r = -0.349$) and SJ PPr 0kg ($r = -0.399$).

Table 4.1 Descriptive and reliability data from jumps and isometric mid-thigh pulls

Kinetic Variables	Mean	SD	95% CI	ICC	CV (%)	Paired T-Test
SJ PPa 0kg (W/kg$^{0.67}$)	229.11	21.83	219.77 – 238.45	0.90	2.62	0.64
SJ PPr 0kg (W/kg)	54.88	5.73	52.43 – 57.33	0.96	2.62	0.70
SJ PPa 20kg (W/kg$^{0.67}$)	227.95	22.97	218.12 – 237.77	0.97	2.28	0.93
SJ PPr 20kg (W/kg)	54.55	5.47	52.21 – 56.89	0.97	2.28	0.90
CMJ PPa 0kg (W/kg$^{0.67}$)	228.00	18.29	220.18 – 235.83	0.95	2.35	0.55
CMJ PPr 0kg (W/kg)	54.57	4.39	52.69 –56.45	0.82	5.05	0.53
CMJ PPa 20kg (W/kg$^{0.67}$)	224.08	21.77	214.77 – 233.39	0.80	5.05	0.88
CMJ PPr 20 kg (W/kg)	53.67	5.67	51.24 – 56.10	0.83	5.05	0.93
IPFa (N/ kg$^{0.67)}$	196.23	24.66	185.68 – 206.78	0.98	2.54	0.12
IRFD at 90ms (N/sec)	4287.76	2985.43	3010.87 – 5564.65	0.89	36.67	0.49
IRFD at 200ms (N/sec)	5442.09	2438.63	4399.06 – 6485.11	0.91	23.26	0.91
IRFD at 250ms (N/sec)	5314.22	1708.15	4583.63 – 6044.81	0.86	18.33	0.92

Notes: SD = Standard deviation, CV = group coefficient of variation, ICC = Intraclass correlation coefficient, SJ PPa = allometrically scaled peak power in a static jump, SJ PPr = peak power relative to body weight in a static jump, CMJ PPa = allometrically scaled peak power in a countermovement jump, CMJ PPr = peak power relative to bodyweight in a countermovement jump, IPFa = allometrically scaled isometric peak force, IRFD = isometric rate of force development

Table 4.2 Descriptive and reliability data for sprint characteristics

Sprint Variables	Mean	SD	95% CI	CV(%)	ICC	Paired T-Test
SV S3 (m/s)	5.54	0.24	5.44 – 5.67	3.35	0.78	0.32
SL S3 (cm)	129.04	8.41	125.41 – 132.68	1.41	0.95	0.83
SF S3 (step/s)	4.31	0.31	4.18 – 4.45	3.54	0.86	0.34
GCT S3 (ms)	157.02	14.14	150.91 – 163.14	2.70	0.94	0.13
SV S6 (m/s)	7.01	0.27	6.90 – 7.13	2.11	0.83	1.00
SL S6 (cm)	157.80	9.85	153.55 – 162.06	1.50	0.96	0.42
SF S6 (step/s)	4.46	0.27	4.34 – 4.58	2.51	0.89	0.55
GCT S6 (ms)	142.04	10.35	137.57 – 146.52	2.40	0.93	0.78
SV S9 (m/s)	8.03	0.27	7.91 – 8.15	1.77	0.84	0.71
SL S9 (cm)	177.43	9.12	173.49 – 181.40	1.20	0.95	0.64
SF S9 (step/s)	4.53	0.23	4.44 – 4.68	2.36	0.86	0.59
GCT S9 (ms)	132.26	9.41	128.19 – 136.33	2.02	0.95	0.86
20m time (sec)	2.95	0.09	2.91-2.98	0.49	0.98	0.22

Notes: SD = Standard deviation, CV = group coefficient of variation, ICC = Intraclass correlation coefficient, SV = Sprint velocity, SL = Step length, SF = Stride Frequency, GCT = Ground contact time, S3 = Step 3, S6 = Step 6, S9 = Step 9

Table 4.3 Relationships between strength-power characteristics and early-acceleration

Kinetic Variables	Vel Step 3	GCT Step 3	SL Step 3	SF Step 3
SJ PPa 0kg (W/kg$^{0.67}$)	.194	-.359	-.130	.219
SJ PPr 0kg (W/kg)	.203	-.493[*]	-.194	.293
SJ PPa 20kg (W/kg$^{0.67}$)	.094	-.089	.096	-.047
SJ PPr 20kg (W/kg)	.096	-.175	.033	.018
CMJ PPa 0kg (W/kg$^{0.67}$)	-.007	-.141	.134	-.141
CMJ PPr 0kg (W/kg)	.003	-.230	.062	-.062
CMJ PPa 20kg (W/kg$^{0.67}$)	-.001	-.176	.137	-.135
CMJ PPr (W/kg)	.009	-.263	.060	-.051
IPFa (N/ kg$^{0.67}$)	.269	-.320	.065	.117
IRFD at 90ms (N/sec)	.023	-.541[*]	-.277	.270
IRFD at 200ms (N/sec)	.026	-.486[*]	-.291	.272
IRFD at 250ms (N/sec)	.128	-.420	-.202	.259

Notes: SJ PPa = allometrically scaled peak power in a static jump, SJ PPr = peak power relative to body weight in a static jump, CMJ PPa = allometrically scaled peak power in a countermovement jump, CMJ PPr = peak power relative to bodyweight in a countermovement jump, IPFa = allometrically scaled isometric peak force, IRFD = isometric rate of force development, * = $p < 0.05$, ** = $p < 0.01$

Table 4.4 Relationships between strength-power variables and mid-acceleration

Kinetic Variables	Vel Step 6	GCT Step 6	SL Step 6	SF Step 6
SJ PPa 0kg (W/kg$^{0.67}$)	.549*	-.289	.003	.334
SJ PPr 0kg (W/kg)	.543*	-.447*	-.153	.490*
SJ PPa 20kg (W/kg$^{0.67}$)	.352	.058	.067	.147
SJ PPr 20kg (W/kg)	.325	-.056	-.044	.244
CMJ PPa 0kg (W/kg$^{0.67}$)	.280	-.004	.049	.121
CMJ PPr 0kg (W/kg)	.257	-.122	-.072	.230
CMJ PPa 20kg (W/kg$^{0.67}$)	.384	-.062	.097	.139
CMJ PPr (W/kg)	.341	-.180	-.039	.250
IPFa (N/ kg$^{0.67)}$)	.294	-.286	-.241	.424
IRFD at 90ms (N/sec)	.157	-.377	-.328	.430
IRFD at 200ms (N/sec)	.241	-.228	-.380	.528*
IRFD at 250ms (N/sec)	.331	-.157	-.359	.562**

Notes: SJ PPa = allometrically scaled peak power in a static jump, SJ PPr = peak power relative to body weight in a static jump, CMJ PPa = allometrically scaled peak power in a countermovement jump, CMJ PPr = peak power relative to bodyweight in a countermovement jump, IPFa = allometrically scaled isometric peak force, IRFD = isometric rate of force development, $*$ = $p < 0.05$, $**$ = $p < 0.01$

Table 4.5 Relationships between strength-power characteristics and late-acceleration

Kinetic Variables	Vel Step 9	GCT Step 9	SL Step 9	SF Step 9
SJ PPa 0kg (W/kg$^{0.67}$)	.241	-.371	-.117	.266
SJ PPr 0kg (W/kg)	.279	-.511*	-.208	.377
SJ PPa 20kg (W/kg$^{0.67}$)	-.094	-.106	.158	-.215
SJ PPr 20kg (W/kg)	-.055	-.195	.074	-.110
CMJ PPa 0kg (W/kg$^{0.67}$)	-.111	-.176	.117	-.191
CMJ PPr 0kg (W/kg)	-.067	-.267	.031	-.081
CMJ PPa 20kg (W/kg$^{0.67}$)	-.115	-.219	.160	-.232
CMJ PPr (W/kg)	-.070	-.308	.064	-.113
IPFa (N/ kg$^{0.67)}$)	.416	-.248	-.225	.489*
IRFD at 90ms (N/sec)	.120	-.444*	-.259	.314
IRFD at 200ms (N/sec)	.013	-.413	-.318	.299
IRFD at 250ms (N/sec)	.059	-.362	-.295	.315

Notes: SJ PPa = allometrically scaled peak power in a static jump, SJ PPr = peak power relative to body weight in a static jump, CMJ PPa = allometrically scaled peak power in a countermovement jump, CMJ PPr = peak power relative to bodyweight in a countermovement jump, IPFa = allometrically scaled isometric peak force, IRFD = isometric rate of force development, $*$ = $p < 0.05$, $**$ = $p < 0.01$

DISCUSSION

The primary purpose of this study was to investigate the relationships between various kinetic variables and sprint characteristics during the early, mid, and late sub-sections of sprint acceleration in Division I male collegiate soccer players. The investigators hypothesized that RFD measures at later time points (e.g. – 200 and 250ms) would show the strongest relationships with GCT during early-acceleration, while RFD measures at earlier time windows (e.g. – 90ms) would display the strongest relationships with GCT during late-acceleration. The rationale behind this hypothesis was that as GCT decreases with greater SV, the athletes might need to generate a higher RFD at earlier time points to generate the GRF necessary to obtain greater sprint speeds (6, 10, 55). Overall, the main findings of this investigation did not support this hypothesis, as IRFD@90, IRFD@200, and IRFD@250 displayed fairly consistent relationships with GCT across multiple acceleration zones. Additionally, these variables also showed steady relationships with SF within each sub-phase of acceleration as well.

For instance, IRFD@90 showed moderate-to-large relationships with GCT (r = -.337 – -.541) and small-to-moderate relationships with SF (r = .270 – .430) across all three sub-phases of acceleration. Additionally, while IRFD@200 (r = -.486) and IRFD@250 (r = -.420) did display moderate correlations with GCT during early-acceleration, both of these variables also displayed moderate relationships during the late acceleration zone as well, which were evident with correlation coefficients of r = -.362 and r = -.420, respectively. In contrast to these trends, however, IRFD@200 and IRFD@250 displayed the strongest relationship with SF during mid-acceleration, with correlation values of r = 0.528 and r = 0.562, respectively. Interestingly, SJ PPr 0kg also showed consistently strong relationships with GCT (r = -.439 – -.511) and SF (r = -.439 – -.511) across all three sub-phases as well. Lastly, SJ PPr 0kg also showed large, positive

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correlations with SV in the mid-acceleration zone ($r = .543$), as well as moderate, negative correlations with 20m times ($r = -.399$). When considered in combination, these findings support the notion that sprint acceleration is likely underpinned by "power-related" qualities (6, 22, 51, 55, 62, 67).

The results of this study are in accordance with a number others that have positively related PP with acceleration performance (1, 14, 40, 49). For example, a study by Peterson et al. (49) found strong, positive relationships with CMJ peak power and 20m speed in collegiate team sport athletes. Cronin and colleagues (14) further supported these findings in reporting strong correlations between SJ PPr at 30kg and sprint speed over distances of 5 and 10m in professional rugby players. Another study by Baker et al. (1) also found strong, negative relationships between PPr during jump squats at various loads and 10m sprint performance in professional rugby athletes as well . Finally, a study by Marques et al. (40) found strong correlations between CMJ PP with a load of 17kg and 10m sprint ability in another population of assorted team sport athletes.

With respect to IRFD, despite the fact that this variable was not consistently correlated with SV, this measure did show steady relationships with GCT and SF during sprint acceleration within each acceleration zone (Tables 4.3, 4.4, 4.5). This may be significant from a practical standpoint, as previous literature has indicated that "faster" team sport athletes display shorter GCT and greater SF in comparison to their "slower" counterparts (28, 37, 45). In particular, Murphy et al. (45) found that faster FSA in a 15m sprint exhibited statistically shorter GCT during steps 1 (0.20 ± 0.02 sec versus 0.23 ± 0.03 sec, $p = 0.01$) and 2 (0.17 ± 0.02 sec versus 0.19 ± 0.02 sec, $p = 0.01$), and also statistically greater average SF (1.82 ± 0.12 Hz versus 1.67 ± 0.24 Hz, $p = 0.01$) in comparison to their slower counterparts. Interestingly, stride length (209 $\pm$

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15cm versus 205 ± 13cm, $p = 0.73$) was not statistically different between these groups. Hewit and colleagues (28) also found similar results with respect to SF and SL in a population of national-level netball players. The investigators concluded that faster netball players actually displayed statistically shorter SL (112 ± 10cm versus 120 ± 6cm, $p = 0.03$) and, although not statistically significant, greater SF (5.45 ± .42Hz versus 5.22 ± .26Hz, $p = 0.13$) in comparison to the slower players over a distance of 2.5m. In contrast to the findings of Murphy et al. (45) and Hewit et al. (28), Lockie et al. (38) found mean SL over 0–5m and 0–10m to be statistically correlated with SV over 0–5m ($r = .502$, $p = 0.011$) and 0–10m ($r = .462$, $p = 0.020$), respectively. Despite this deviation from previous findings, Lockie and colleagues (38) did find similar results as those found by Murphy et al. (45) and Hewit et al. (28) with respect to GCT, as this sprint metric over 0–5m (r = -.506, $p = 0.010$) and 0–10m (r = -.477, $p = 0.016$) intervals showed statistically significant, negative relationships with SV over 5–10m. Regardless of expressing greater SL or SF, it appears that a commonality amongst all these investigations is that faster athletes produce force more efficiently, likely due to a superior RFD, which may result in shorter GCT.

The findings of the current study also conflicted with the investigators' hypothesis that GCT would be closely associated with RFD measures collected within a similar time window (6, 10, 55). For example, the investigators believed that contact times closest to 200ms, such as those seen during early acceleration, would show the strongest relationship with IRFD@200. Theoretically, this concept makes sense, as the athlete likely has to apply force at a greater rate as contact time diminishes at greater sprint speeds (6, 10, 55). Contrary to this notion, the results of this study suggest that this is not the case. Specifically, the strongest correlations between IRFD@90 and GCT were found in the early acceleration zone ($r = -.541$), where contact times

were the longest (Table 2.3). Additionally, the relationships between SJ PP 0kg and GCT also remained consistent across each portion of acceleration and did not show the progressive increase one would expect at further sprint distances (Tables 4.3, 4.4, 4.5). Therefore, these results imply that the shorter GCT inherent to greater SV may not lead to a strengthened the relationship with RFD at earlier time points or PP, as previously believed (6, 10, 55). In fact, our findings infer that these instantaneous variables may be more relevant in the early stages of acceleration rather than the later phases.

A possible explanation for this result may be the found by examining the force-velocity curve of the stance phase during sprint acceleration, which is composed of an eccentric, "braking" portion and a concentric, "propulsive" portion (32, 43, 44). According to Hunter et al. (32) and Morin et al. (44), the duration of the braking phase appears to be well below the 90ms threshold, and likely accounts for ≤20% of contact time (31, 43). When these observations are considered in conjunction with those of the current study, it can be hypothesized that faster athletes may express a higher RFD at earlier time points (e.g. - ≤90ms), thus attenuating eccentric, braking forces at a superior rate in comparison to their slower counterparts. Consequently, this may allow these athletes to develop a greater eccentric force from which to initiate the concentric portion of the stance phase, essentially "potentiating" propulsive IP during the latter portion of ground contact. By creating a greater propulsive IP (44), these athletes may generate a higher GRF, thus facilitating greater SV (66). In addition to accentuating the significance of RFD, this concept further highlights the potential importance of musculotendonous unit (MTU) stiffness (7) and leg stiffness (6), as these qualities may be advantageous in developing a greater RFD (7) and, subsequently, sprint acceleration (6).

Furthermore, expressing high RFD at earlier time windows may be more critical during early-acceleration, as the braking portion of the stance phase appears to be shortest during the first few steps of each effort (43, 44). This is likely due to foot placement, as these steps often contact the ground behind the center of mass during this sub-section of acceleration (46). As a result, the athlete may have less time to equalize body mass and develop greater eccentric force to begin the concentric portion of the stance phase (43). Although this hypothesis has yet to be thoroughly investigated, the results in a recent study by Wang and colleagues (64) may support this notion, as IRFD during an IMTP at time windows of 30 and 50ms showed strong, negative correlations with 5m sprint performance in collegiate rugby players. Based on these observations, the ability to express a high RFD at earlier time points is likely a critical performance variable during both acceleration and maximum velocity. Keeping these considerations in mind, the importance of developing high forces at later time points should not be overlooked, as IRFD@200 and IRFD@250 also displayed moderate-to-strong, negative relationships with GCT during early- and late-acceleration, as well as strong, positive relationships with SF during mid-acceleration (Tables 4.3, 4.4, and 4.5). These time points may be instrumental in developing the latter half of propulsive IP during the stance phase, thus making them a key component in developing greater SV during acceleration as well.

From a training perspective, the results of the present study provide a number of considerable implications. Most notably, these findings highlight the importance of RFD and PP within each acceleration zone. However, the crucial role of MS in the development of these fitness characteristics cannot be overlooked, as it is well documented that stronger athletes display superior RFD (4, 25, 30, 56, 60) and PP (13, 57, 58, 60). Also, stronger athletes have been shown to develop greater levels of eccentric force (13), which may enhance their ability to

produce high forces upon ground contact, potentially heightening the propulsive portion of stance phase. Given the impact of these performance capabilities on sprint acceleration, the development of MS should remain a priority when aiming to enhance this skill. Secondly, these findings also support the critical nature of addressing the entire force-velocity curve to improve sprint acceleration. This is evident when viewing the consistent relationship between each IRFD measure and GCT throughout sprint acceleration. Subsequently, improvements in PP and RFD can be achieved by shifting this curve in a positive direction (24).

This objective appears to be effectively met by using a "mixed methods" training approach (24, 47, 60). Theoretically, using a combination of heavy (≥80% 1RM) and light (<50% 1RM) loads may shift both sides of the force-velocity curve in a positive direction (24, 26, 60). When combined with block periodization and phase potentiation (18, 19), multiple studies and reviews have shown combination training to be a more effective method in developing RFD (24, 30, 48, 60) and PP (24, 27, 30, 47, 60) than heavy resistance training or power-training alone. Ultimately, the use of both training modalities in the proper sequence may enhance sprint acceleration by developing the force-producing capabilities necessary to express higher propulsive GRF.

Although there is a wealth of literature relating greater levels of MS (1, 11, 16, 41, 52), PP (1, 15, 54), and RFD (22, 54, 62, 64, 65) to sprint performance, the author is unaware of any study that has investigated the way in which these qualities effect the sprint characteristics in FSA. Previous studies have compared the differences in sprint characteristics between "fast" and "slow" FSA during acceleration (28, 45), but have not done so with respect to their strength-power capabilities or within different sub-sections of acceleration. Based on the results of the current study, one may hypothesize that stronger and more powerful FSA likely demonstrate

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shorter GCT and greater SF, which might facilitate greater SV. However, this study did not make such comparisons. Consequently, future research should aim to compare the sprint characteristics between "strong" and "weak" FSA during the early-, mid-, and late-acceleration zones. A comparison between FSA who display "higher power outputs" versus "lower power outputs" within these sub-phases is also warranted as well.

PRACTICAL APPLICATION

The results of this study support the notion that developing high RFD and PP may positively enhance sprint acceleration by decreasing GCT and increasing SF. Practitioners should consider utilizing a combination of "heavy" and "light" exercises to concurrently develop MS in addition to these power-associates. Furthermore, organizing these training methods through the use of block periodization and phase potentiation may further enhance these training adaptations (18, 19). By effectively managing the training process, athletes and practitioners may optimize RFD and PP, thereby increasing the likelihood of achieving a desirable transfer of training effect.

References

1.   Baker D, Nance, S. The relation between running speed and measures of strength and power in professional rugby league players. *J Strength Cond Res* 13: 230-235, 1999.
2.   Bangsbo J, Norregaard L, and Thorso F. Activity profile of competition soccer. *Can J Sport Sci* 16: 110-116, 1991.
3.   Barr MJ, Sheppard JM, and Newton RU. Sprinting kinematics of elite rugby players. *Journal of austrailian strength and conditioning* 21: 14-20, 2013.
4.   Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *J Sports Med Phys Fitness* 53: 573-581, 2013.
5.   Bellon CR. The relationship between strength, power, and sprint acceleration in field sport athletes in: *Exercise and Sport Science*. East Tennessee State University, 2016.
6.   Bret C, Rahmani A, Dufour AB, Messonnier L, and Lacour JR. Leg strength and stiffness as ability factors in 100 m sprint running. *J Sports Med Phys Fitness* 42: 274-281, 2002.
7.   Brughelli M and Cronin J. A review of research on the mechanical stiffness in running and jumping: methodology and implications. *Scandinavian journal of medicine & science in sports* 18: 417-426, 2008.
8.   Cappadona J. Kinematic and spatiotemporal analysis between sprint drills and maximal sprinting, in: *Physical Therapy & Human Movement Science*. Fairfield University: Sacred Heart University, 2013, p 52.
9.   Carlock JM, Smith SL, Hartman MJ, Morris RT, Ciroslan DA, Pierce KC, Newton RU, Harman EA, Sands WA, and Stone MH. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *J Strength Cond Res* 18: 534-539, 2004.
10.   Chelly SM and Denis C. Leg power and hopping stiffness: relationship with sprint running performance. *Med Sci Sports Exerc* 33: 326-333, 2001.
11.   Comfort P, Bullock N, and Pearson SJ. A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *J Strength Cond Res* 26: 937-940, 2012.
12.   Comfort P, Haigh A, and Matthews MJ. Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *J Strength Cond Res* 26: 772-776, 2012.
13.   Cormie P, McGuigan MR, and Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 42: 1566-1581, 2010.
14.   Cronin J, Hansen, K. Resisted sprint training for the acceleration phase of sprinting. *Strength & conditioning Journal* 28, 2006.
15.   Cronin JB and Hansen KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349-357, 2005.
16.   Cunningham DJ, West DJ, Owen NJ, Shearer DA, Finn CV, Bracken RM, Crewther BT, Scott P, Cook CJ, and Kilduff LP. Strength and power predictors of sprinting performance in professional rugby players. *J Sports Med Phys Fitness* 53: 105-111, 2013.
17.   Delecluse C. Influence of strength training on sprint running performance. Current findings and implications for training. *Sports Med* 24: 147-156, 1997.

18. DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part 2: Practical and applied aspects. *Journal of sport and health science* 4: 318-324, 2015.

19. DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part I: Theoretical aspects. *Journal of sport and health science* 4: 308-317, 2015.

20. Duthie GM, Pyne DB, Marsh DJ, and Hooper SL. Sprint patterns in rugby union players during competition. *J Strength Cond Res* 20: 208-214, 2006.

21. Faude O, Koch T, and Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci* 30: 625-631, 2012.

22. Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, and Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Res Sports Med* 14: 205-214, 2006.

23. Gregson W, Drust B, Atkinson G, and Salvo VD. Match-to-match variability of high-speed activities in premier league soccer. *Int J Sports Med* 31: 237-242, 2010.

24. Haff G and Nimphius S. Training principles for power. *Strength & conditioning Journal* 34: 2-12, 2012.

25. Haff GG, Stone MH, O'Bryant HS, Harman EA, Dinan C, and Johnson R. Force-time dependent characteristics of dynamic and isometric muscle action *Journal of strength and conditioning research* 11: 269-272, 1997.

26. Hakkinen K. Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electromyography and clinical neurophysiology* 34: 205-214, 1994.

27. Harris GR, Stone, M. H., O'Bryant, H. S., Proulx, C. M., Johnson, R. L. Short-term performance effects of high power, high force, or combined weight training methods. *J Strength Cond Res* 14, 2000.

28. Hewit JK, Cronin JB, and Hume PA. Kinematic factors affecting fast and slow straight and change-of-direction acceleration times. *J Strength Cond Res* 27: 69-75, 2013.

29. http://sportsci.org/resource/stats/effectmag.html. Accessed January/2015.

30. Hornsby WG. A systematic approach to the monitoring of competitive weightlifters, in: *Exercise and Sport Science*. Johnson City, TN: East Tennessee State University, 2013.

31. Hunter JP, Marshall RN, and McNair PJ. Segment-interaction analysis of the stance limb in sprint running. *J Biomech* 37: 1439-1446, 2004.

32. Hunter JP, Marshall RN, and McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech* 21: 31-43, 2005.

33. Jovanovic M, Sporis G, Omrcen D, and Fiorentini F. Effects of speed, agility, quickness training method on power performance in elite soccer players. *J Strength Cond Res* 25: 1285-1292, 2011.

34. Kinser AM, Ramsey MW, O'Bryant HS, Ayres CA, Sands WA, and Stone MH. Vibration and stretching effects on flexibility and explosive strength in young gymnasts. *Med Sci Sports Exerc* 40: 133-140, 2008.

35. Kivi D and Alexander M. A kinematic comparison of the running A and B drills with sprinting, in: *Physical Education and Recreation Studies*. Manitoba, Canada: University of Manitoba, 1997, p 198.

36. Kraska JM, Ramsey MW, Haff GG, Fethke N, Sands WA, Stone ME, and Stone MH. Relationship between strength characteristics and unweighted and weighted vertical jump height. *Int J Sports Physiol Perform* 4: 461-473, 2009.

37. Lockie RG, Murphy AJ, Knight TJ, and Janse de Jonge XA. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res* 25: 2704-2714, 2011.

38. Lockie RG, Murphy AJ, Schultz AB, Jeffriess MD, and Callaghan SJ. Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *J Strength Cond Res* 27: 2494-2503, 2013.

39. Markovic G and Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med* 40: 859-895, 2010.

40. Marques MC, Gil H, Ramos RJ, Costa AM, and Marinho DA. Relationships between vertical jump strength metrics and 5 meters sprint time. *J Hum Kinet* 29: 115-122, 2011.

41. McBride JM, Blow D, Kirby TJ, Haines TL, Dayne AM, and Triplett NT. Relationship between maximal squat strength and five, ten, and forty yard sprint times. *J Strength Cond Res* 23: 1633-1636, 2009.

42. Meir R, Colla P, and Milligan C. Impact of the 10-metre rule change on professional rugby league: Implications for training. *Strength & conditioning Journal* 23: 42-46, 2001.

43. Mero A. Force-time characteristics and running vleocity of male sprinters acceleration phase of sprinting. *Res Q Exerc Sport* 59: 94-98, 1988.

44. Morin JB, Slawinski J, Dorel S, de Villareal ES, Couturier A, Samozino P, Brughelli M, and Rabita G. Acceleration capability in elite sprinters and ground impulse: Push more, brake less? *J Biomech* 48: 3149-3154, 2015.

45. Murphy AJ, Lockie RG, and Coutts AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sports Sci Med* 2: 144-150, 2003.

46. Nagahara R, Matsubayashi T, Matsuo A, and Zushi K. Kinematics of transition during human accelerated sprinting. *Biol Open* 3: 689-699, 2014.

47. Newton RU and Kraemer WJ. Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength & conditioning Journal* 16: 20-31, 1994.

48. Painter KB, Haff GG, Ramsey MW, McBride J, Triplett T, Sands WA, Lamont HS, Stone ME, and Stone MH. Strength gains: block versus daily undulating periodization weight training among track and field athletes. *Int J Sports Physiol Perform* 7: 161-169, 2012.

49. Peterson MD, Alvar BA, and Rhea MR. The contribution of maximal force production to explosive movement among young collegiate athletes. *J Strength Cond Res* 20: 867-873, 2006.

50. Rienzi E, Drust B, Reilly T, Carter JE, and Martin A. Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *J Sports Med Phys Fitness* 40: 162-169, 2000.

51. Seitz LB, Barr M, and Haff GG. Effects of Sprint Training With or Without Ball Carry in Elite Rugby Players. *Int J Sports Physiol Perform*, 2014.

52. Seitz LB, Reyes A, Tran TT, Saez de Villarreal E, and Haff GG. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Med* 44: 1693-1702, 2014.

53. Siff MC. *Supertraining.* Rome: Ultimate Athlete Concepts, 2009.

54. Sleivert G and Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *Eur J Appl Physiol* 91: 46-52, 2004.

55. Smirniotou A, Katsikas C, Paradisis G, Argeitaki P, Zacharogiannis E, and Tziortzis S. Strength-power parameters as predictors of sprinting performance. *J Sports Med Phys Fitness* 48: 447-454, 2008.

56. Sole CJ. Analysis of countermovement jump force-time curve phase characteristics in athletes, in: *Exercise and Sport Science*. Johnson City, TN: East Tennessee State University, 2015.

57. Stone MH, Moir, G., Glaister, M., Sanders, R. How much strength is necessary? *Phys Ther Sport* 3: 88-96, 2002.

58. Stone MH, O'Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140-147, 2003.

59. Stone MH, Sands WA, Pierce KC, Carlock J, Cardinale M, and Newton RU. Relationship of maximum strength to weightlifting performance. *Med Sci Sports Exerc* 37: 1037-1043, 2005.

60. Stone MH, Stone, M., Sands, W. A. *Principles and Practice of Strength Training.* Champaign, IL: Human Kinetics, 2007.

61. Taber C, Bellon CR, Abbott H, and Bingham GE. Roles of maximal strength and rate of force development in maximizing muscular power. *Strength & conditioning Journal* 38: 71-78, 2016.

62. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between isometric mid-thigh pull variables and sprint change of direction in collegiate athletes. *Journal of trainology* 4: 6-10, 2015.

63. Vigne G, Gaudino C, Rogowski I, Alloatti G, and Hautier C. Activity profile in elite Italian soccer team. *Int J Sports Med* 31: 304-310, 2010.

64. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, La Monica MB, Beyer KS, Church DD, Fukuda DH, and Jeffrey SR. Isometric Mid-Thigh Pull Correlates with Strength, Sprint and Agility Performance in Collegiate Rugby Union Players. *J Strength Cond Res*, 2016.

65. Weyand PG, Sandell RF, Prime DN, and Bundle MW. The biological limits to running speed are imposed from the ground up. *J Appl Physiol* 108: 950-961, 2010.

66. Weyand PG, Sternlight DB, Bellizzi MJ, and Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 89: 1991-1999, 2000.

67. Young W, McLean B, and Ardagna J. Relationship between strength qualities and sprinting performance. *J Sports Med Phys Fitness* 35: 13-19, 1995.

CHAPTER 5

THE EFFECT OF STRENGTH AND POWER ON ACCELERATION CHARACTERISTICS
IN DIVISION I MEN'S SOCCER PLAYERS

Authors: [1]Christopher R. Bellon, [1]Brad H. DeWeese, [1]Kimitake Sato, [2]Kenneth P. Clark, [1]Michael H. Stone

Affiliations: [1]Center of Excellence for Sport Science and Coach Education, Department of

Exercise and Sport Sciences, East Tennessee State University, Johnson City, TN, USA

[2]Department of Kinesiology, West Chester University, West Chester, PA, USA

Abstract

Purpose: The purpose of this study was to compare the sprint characteristics of "strong" versus "weak" athletes, as well as athletes who generate "high power outputs" versus "low power outputs", during early-, mid-, and late-acceleration. **Methods:** Twenty-one Division I men's soccer players performed unloaded static jumps (SJ) and isometric mid-thigh pulls (IMTP) on dual force platforms. Peak power relative to body mass (SJ PPr 0kg) was measured for the SJ, while allometrically scaled peak force (IPFa) was recorded for the IMTP. Lastly, 20m sprints were performed through an optical measurement system, which recorded sprint velocity (SV), step length (SL), step frequency (SF), and ground contact time (GCT) within each zone. 2x3 repeated measures ANOVA were used to compare these sprint characteristics between strong versus weak athletes, as well as those generating higher power outputs versus lower power outputs during early-, mid-, and late-acceleration. **Results:** There were no statistically significant strength level main effects for SV ($p = 0.760$), SL ($p = 0.152$), SF ($p = 0.342$), or GCT ($p = 0.701$). In contrast, there were statistically significant power level main effects for SV ($p = 0.027$) and GCT ($p = 0.041$), but not SL ($p = 0.953$) or SF ($p = 0.213$). *Post Hoc* analysis revealed that the high power group achieved statistically greater SV during mid- ($p = 0.040$) and late-acceleration ($p = 0.041$), as well as shorter GCT during mid-acceleration ($p = 0.026$) in comparison to the low power group. Effect sizes indicated that the strong and high power groups achieved greater SV by expressing greater SF and shorter GCT compared to the weak and lower power groups, respectively. **Conclusion:** Stronger, more powerful athletes may accelerate faster than their weaker, less-powerful counterparts by maximizing SF and minimizing GCT.

Key Words: *rate of force development, sprinting, speed development*

INTRODUCTION

Sprint acceleration is recognized as one of the most critical skills to develop in field sport athletes (FSA) such as soccer and rugby players (2, 6, 26). Not only has acceleration been shown to differentiate levels of playing ability (8, 20-23), but it also appears to play a role in key points of gameplay such as evading a defender or creating scoring opportunities (19, 37, 40). Common methods of developing this skill include resistance training, plyometrics, resisted sprinting, and sprint drills (11, 14, 35). The majority of these tools, particularly the latter three mentioned, attempt to exploit the principle of specificity by overloading movement patterns similar to those employed during sprint acceleration. However, the importance of resistance training should not be undervalued, as a wealth of investigations have shown athletes who showcase greater sprint acceleration often possess higher levels of maximal strength (MS) (9, 13, 36, 41), peak power (PP) (1, 12, 13, 42), and rate of force development (RFD) (33, 34, 49, 50). In fact, an argument can be made that resistance training provides a level of "kinetic specificity", as the high ground reaction forces (GRF) inherent to sprinting may be similar to those achieved with various resistance training practices (32).

This notion was recently supported in a recent study by Bellon (4), who explored the relationship between power-related variables and key sprint characteristics during the early, mid, and late sub-sections of sprint acceleration in collegiate men's soccer players. The findings of this investigation revealed that PP relative to body mass during an unloaded static jump (SJ PPr 0kg) and RFD at 90ms (RFD@90) showed moderate-to-strong correlations with ground contact time (GCT) during each phase of acceleration. Additionally, these variables, as well as RFD at 200 (RFD@200) and 250ms (RFD@250), also showed moderate-to-strong correlations with step frequency (SF) during mid-acceleration. Based on these results, it can be hypothesized that

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collegiate men's soccer players demonstrating higher levels of PP and RFD may attain greater sprint velocity (SV) during acceleration by expressing higher forces over shorter GCT, thus facilitating greater SF. However, it is also important to consider that athletes who display higher levels of MS often exhibit greater PP (10, 44, 45, 47) and RFD (3, 25, 29, 43, 47). Accordingly, stronger athletes may also demonstrate similar acceleration patterns as those proposed by Bellon (4) as well.

Interestingly, multiple studies have shown faster team sport athletes to demonstrate greater acceleration ability by exhibiting shorter GCT and greater SF in comparison to their slower counterparts (27, 30, 38). However, none of these investigations compared the strength and power capabilities of the "fast" versus the "slow" athletes. Therefore, the mechanisms underpinning these kinematic differences remain unknown. Such information is pertinent to understanding how strength and power may affect the spatiotemporal profiles of FSA. Therefore, the primary purpose of this study is to compare the sprint characteristics of "strong" versus "weak" Division I collegiate men's soccer players during early, mid, and late acceleration. Additionally, the secondary purpose of this study is to compare the same acceleration variables in players who are able to generate "higher power outputs" versus "lower power outputs". Considering the wealth of evidence relating strength-power capabilities to SF and GCT (4, 27, 30, 38), the investigators hypothesize that the strong and higher power output groups will display faster SF and shorter GCT in comparison to their weak and lower power output counterparts, respectively.

METHODS

Experimental Approach to the Problem

The athletes completed unloaded static jumps (SJ), isometric mid-thigh pulls (IMTP), and 20m maximal-effort sprints over a single testing session. The athletes were separated in strong and weak groups based on allometrically scaled peak force (IPFa) values from the IMTP. Similarly, the athletes were also divided into groups that demonstrated higher power outputs and lower power outputs based on SJ PPr 0kg values. These variables were chosen as differentiating criteria based on the findings of Bellon (4). 2x3 repeated measures ANOVA were used to compare the sprint characteristics during steps 3, 6, and 9 of the 20m sprints between these groups. Each of these measurements was made as a part of an on-going athlete monitoring program.

Participants

The athletes included in this study were twenty-one Division I male collegiate soccer players (age = 20.7 ± 1.2 years, height = 179.38 ± 6.09cm, body mass = 76.4 ± 6.5kg). All athletes met the inclusion criteria of having at least one year of resistance training experience and two years of soccer experience. Additionally, each individual read and signed a written informed consent form prior to participating in any testing procedures. This study was approved by the East Tennessee State University Institutional Review Board.

Testing Procedures

Warm-Up

Prior to performing any strength, power, or speed testing, each athlete participated in a standardized warm-up protocol. This procedure included 25 jumping jacks and a series of mid-

thigh clean pulls with a standard 20kg barbell (Werksan, Turkey). Specifically, the mid-thigh

clean pulls were performed for 1 set of 5 repetitions and 3 sets of 5 repetitions with loads of 20kg

and 60kg, respectively.

Static Jump Testing

Following the completion of the standardized warm-up, each athlete participated in

vertical jump testing, which consisted of unloaded SJ using a 0kg (PVC pipe) bar. The athletes

performed each jump by holding the 0kg bar just below the seventh cervical vertebra (7, 45).

Each maximum effort jump trial was performed on 91.4x91.4cm dual force platforms (Rice Lake

Weighing Systems, Rice Lake, WI) with sampling rates of 1000 Hz. In preparation for the

maximum effort trials, each athlete was instructed to firmly grasp the 0kg bar and assume a squat

position with a 90° knee angle, which was measured using a handheld goniometer (Figure 1).

Once this position was acquired, the athletes completed practice jumps at 50% and 75% of

perceived maximum effort. It is important to note that the athletes were instructed to be still

when holding the "ready position" to eliminate any use of the stretch-shortening cycle (SSC)

(25). For the maximum effort SJ trials, the athletes were instructed to firmly hold the 0kg bar,

step onto the force platforms, and assume the "ready position". Upon acquiring the proper

position, a countdown of "3-2-1 Jump" was given. The average of two trials within 2cm was

used for analysis for each load. Additional trials were performed if the athlete appeared to put

forth less than a maximum effort, used a SSC, or if the difference in jump height between

attempts was greater than 2cm. A rest period of 1-minute was provided between jump trials.

SJ force-time data obtained from the force plates were filtered using a digital low-pass

Butterworth filter with a cutoff frequency of 10 Hz and analyzed using a custom-built Labview

program (LabView 8.5.1, 8.6, and 2010, National Instruments Co., Austin, TX). Peak power

(PP) was calculated from the power-time data from each force plate. Relative peak power (PPr) was calculated by simply dividing PP by the athlete's body mass. The first timing gate was stationed at a lower position of 40cm, whereas the second was at a higher position of 110cm. The rationale for these positions was to ensure that the athlete's hands did not prematurely trigger the timing gate prior to initiating their start.

Figure 5.1 Static jump "ready position"

Isometric Mid-Thigh Pull Testing

Following the completion of vertical jump testing, the athletes were positioned inside a power rack and guided into the appropriate joint angles to properly perform the test. Body angles will vary from one individual to the next due to anthropometrical differences, but each athlete will achieve knee and hip angles between 125-135 and 145-155 degrees, respectively (3) (Figure 2). Each pulling trial was performed while standing on 91.4x91.4cm dual force platforms (Rice Lake Weighing Systems, Rice Lake, WI) with sampling rates of 1000 Hz. These platforms were

positioned inside a custom-built power rack that allowed the bar to be adjusted to any height. Once the permissible body positions were achieved, the athletes were given lifting straps and performed 2 practice repetitions at 50% and 75% perceived maximal effort. Prior to performing the first trial at maximal intensity, the athlete's hands were secured to the bar using athletic tape. Finally, the athlete was placed back into the proper pulling position and awaited the tester's countdown of "3, 2, 1 Pull". The testers gave verbal encouragement for the duration of every maximal effort attempt. The attempts were terminated when the athlete displayed a steady decrease or plateau in force output. Following each pull, the athletes were given a minimum rest period of 3-minutes.

IMTP force-time data obtained from the force plates were filtered using a digital low-pass Butterworth filter with a cutoff frequency of 10 Hz and analyzed using a custom-built Labview program (LabView 8.5.1, 8.6, and 2010, National Instruments Co., Austin, TX). IPFa was calculated using the following allometric expression: Peak Force/(Body Mass $(kg)^{.67}$) (46).

Figure 5.2 Isometric mid-thigh pull position

20-Meter Sprints

Following IMTP testing, the athletes underwent an additional standardized warm-up consisting of light jogging, brief dynamic stretches, and submaximal build-ups at 50% and 75% of perceived maximum effort. Upon completion of the warm-up protocol, each athlete performed 3 maximum-effort 20m sprints with a 3-5 minute rest period between each trial. Each trial was initiated from a crouched starting position 30cm behind the starting line (Figure 3). This 30cm buffer was used to ensure the athletes' knees did not prematurely trigger the electronic timing gates. 20m sprint times were recorded using electronic timing gates (Brower Timing Systems, Draper, UT). The first timing gate was stationed at a lower position of 40cm, whereas the second was at a higher position of 110cm. The rationale for these positions was to ensure that the athlete's hands did not prematurely trigger the timing gate prior to initiating their start. Sprint characteristics were recorded using the OptoJump Next system (Microgate, Bolzano, Italy). This

optical measurement system is composed of transducer and receiver bars, which are each 1m in length. Each bar consists of 32 infrared light emitting bodies (LED) collecting at a sampling frequency of 1000 Hz. Sprint characteristics measured included SV, SL, SF, and GCT for steps 3, 6, and 9, which were chosen to represent the early- (0-2.5m), mid-, (2.5-6m) and late-acceleration (6-12m) zones, respectively. These steps were selected to represent their associated sub-sections based on the results of Bellon (4). The average value of each sprint characteristic from the two fastest trials was used for analysis.

Figure 5.3 Starting position for the 20m-sprint test

Statistical Analysis

The test-retest reliability of measurements was assessed using intraclass correlation coefficients (ICC) and coefficients of variation (CV). 95% confidence intervals were also used to quantify the precision of measurement for all variables. Athletes who displayed values above the group median in IPFa (median = 192.22 N/kg$^{.67}$) and SJ PPr 0kg (54.75 N/kg) were assigned to

strong (N = 11) and higher power output (N = 10) groups, while those who expressed values

below this threshold were assigned to the weak (N = 10) and lower power output (N = 11)

groups. An independent samples t-test was performed to ensure that these groups were in fact

statistically different from one another. Statistical significance was set to $p < 0.05$.

A 2 x 3 repeated measures ANOVA was used to determine if the sprint variables were

statistically different between the strong and weak groups within each sprint zone. Additionally,

a 2 x 3 repeated measures ANOVA was also used to determine if the sprint variables were

statistically different between the higher power and lower power groups within each sprint zone

as well. If the assumption of sphericity was violated, Greenhouse-Geiser adjusted values were

used. When necessary, *post*-hoc analyses were performed using the Bonferroni correction

technique. Cohen's *d* effect sizes were calculated and interpreted as trivial, small, moderate,

large, very large, and nearly perfect with values of 0.0, 0.2, 0.6, 1.2, 2.0, and 4.0, respectively,

based on the scale by Hopkins (28). Statistical power (*c*) was also calculated. All statistical

analysis were calculated using SPSS version 21 (IBM, New York, NY) and statistical

significance was set to $p < 0.05$ for all analyses.

RESULTS

"Strong" versus "Weak" Comparison

An independent samples t-test revealed the difference in IPFa between the strong and

weak groups to be statistically significant ($t_{19} = 8.111$, $p = 0.000$). Descriptive data for both

groups can be found in Table 5.1. All sprint variables were found to be within an acceptable

range of reliability for the strong and weak groups with ICC values of 0.89 – 0.99 and .87 – .99,

respectively. CV values also ranged from of 1.32 – 3.40% and 0.76 – 4.00%, respectively. IPFa

for both the strong and weak groups was also found to be reliable with each group displaying

ICC values of 0.97 and 0.93, respectively. CV values were also found to be reliable at 2.23% and

2.90%, respectively. Statistically significant main effects for acceleration zone existed for SV

($F_{2, 38}$ = 625.58, p = 0.000, c = 1.000), SL ($F_{2, 38}$ = 1030.68, p = 0.000, c = 1.000), SF ($F_{2, 38}$ =

9.78, p = 0.000, c = 0.975), and GCT ($F_{2, 38}$ = 98.61, p = 0.000, c = 1.000). *Post Hoc* analysis

revealed that SV, SL, and SF in acceleration zone 3 were statistically greater than acceleration

zones 1 and 2 (Table 5.6). Additionally, SV, SL, and SF in acceleration zone 2 were also

statistically greater than zone 1 (Table 5.6). In contrast, GCT in acceleration zone 3 was

statistically shorter than in acceleration zones 1 and 2. GCT in acceleration zone 2 was also

statistically shorter than zone 1 (Table 5.6). 95% confidence intervals for the difference in SV,

SL, SF, and GCT between zones 1, 2, and 3 can be found in the Tables 5.12-5.15 in Appendix C,

respectively. There were no statistically significant main effects for strength levels for SV, SL,

SF, or GCT. Additionally, there were no statistically significant strength level x acceleration

zone interaction effects for SV, SL, SF, or GCT.

Table 5.1 Descriptive data for "strong" versus "weak" groups

Variable	Mean	SD	95% CI Lower Bound	95% CI Upper Bound
Strong (N/kg$^{.67}$)	216.44	4.86	213.57	219.31
Weak (N/kg$^{.67}$)	174.00	5.01	170.91	177.09

Figure 5.4 Sprint velocity differences between "strong" versus "weak" athletes

Table 5.2 Sprint velocity differences between "strong" versus "weak" athletes

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Strong (m/sec)	5.59 ± 0.28	5.43 -5.75	7.06 ± 0.31	$6.88 - 7.23$	8.11 ± 0.25	$7.95 - 8.27$
Weak (m/sec)	5.47 ± 0.23	$5.30 - 5.64$	6.92 ± 0.22	$6.74 - 7.10$	7.89 ± 0.25	$7.72 - 8.06$

Figure 5.5 Step length differences in "strong" versus "weak" athletes

Table 5.3 Step length differences in "strong" versus "weak" athletes

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Strong (cm)	128.77 ± 6.80	123.68 – 133.87	155.77 ± 10.23	151.72 – 164.68	175.77 ± 8.90	170.36 – 181.18
Weak (cm)	127.00 ± 9.29	121.65 – 132.35	158.2 ± 9.27	151.72 – 164.68	176.75 ± 8.18	171.08 – 182.42

Figure 5.6 Step frequency differences between "strong" versus "weak" athletes
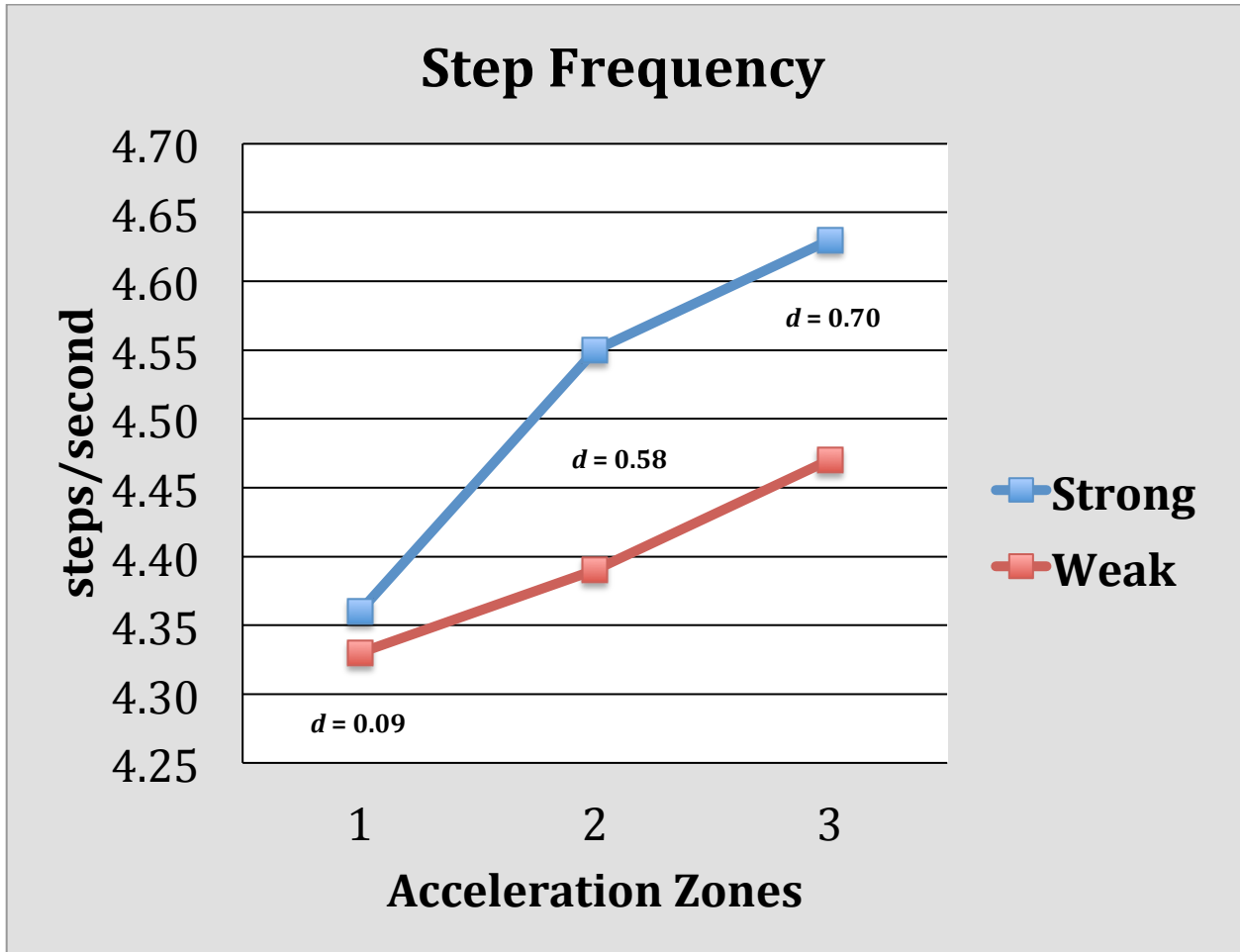
Table 5.4 Step frequency differences between "strong" versus "weak" athletes

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Strong (steps/sec)	4.36 ± 0.30	$4.16 - 4.56$	4.55 ± 0.28	$4.37 - 4.72$	4.63 ± 0.23	$4.48 - 4.77$
Weak (steps/sec)	4.33 ± 0.35	$4.11 - 4.54$	4.39 ± 0.27	$4.21 - 4.57$	4.47 ± 0.23	$4.32 - 4.63$

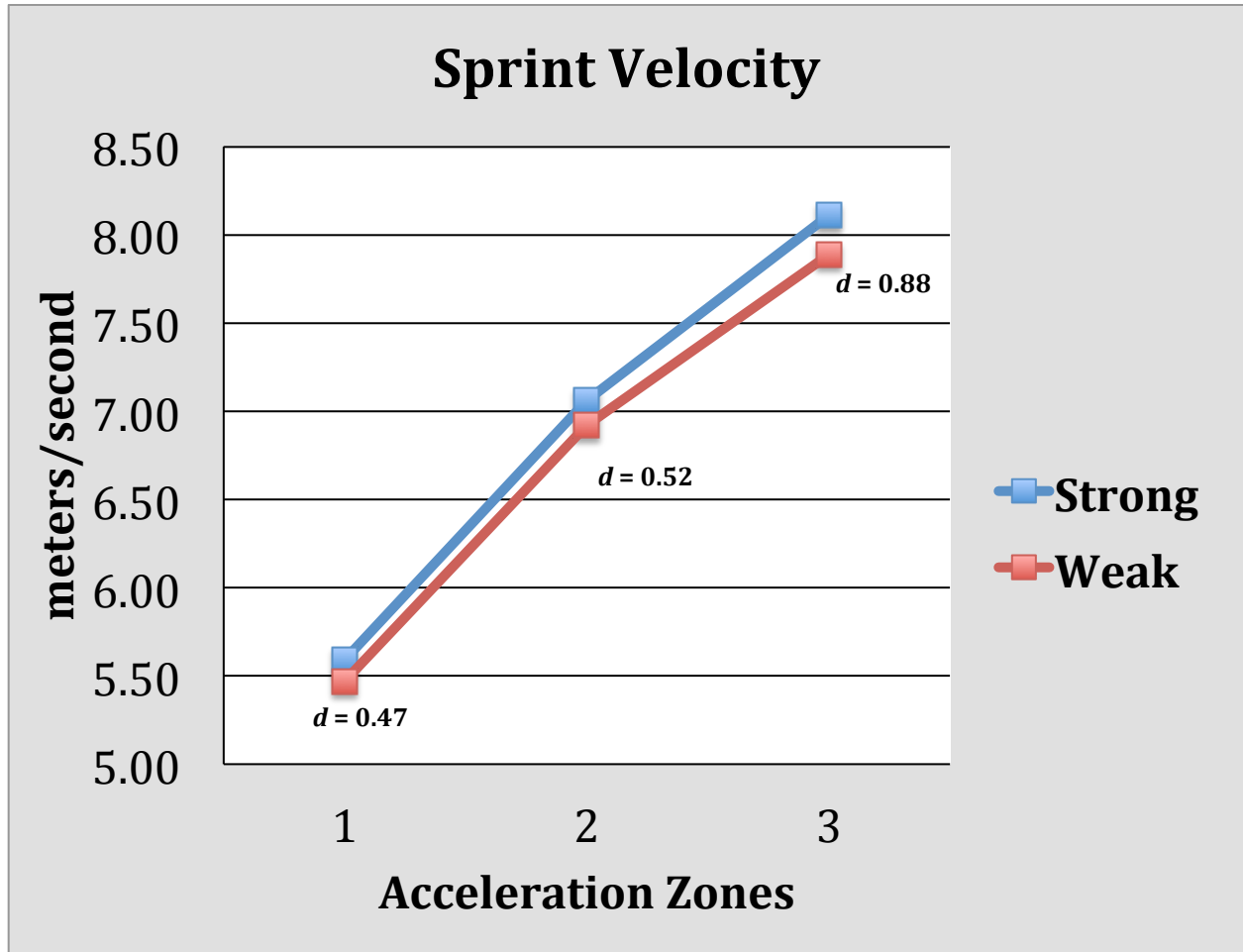*Figure 5.7* Ground contact time difference between "strong" versus "weak" athletes

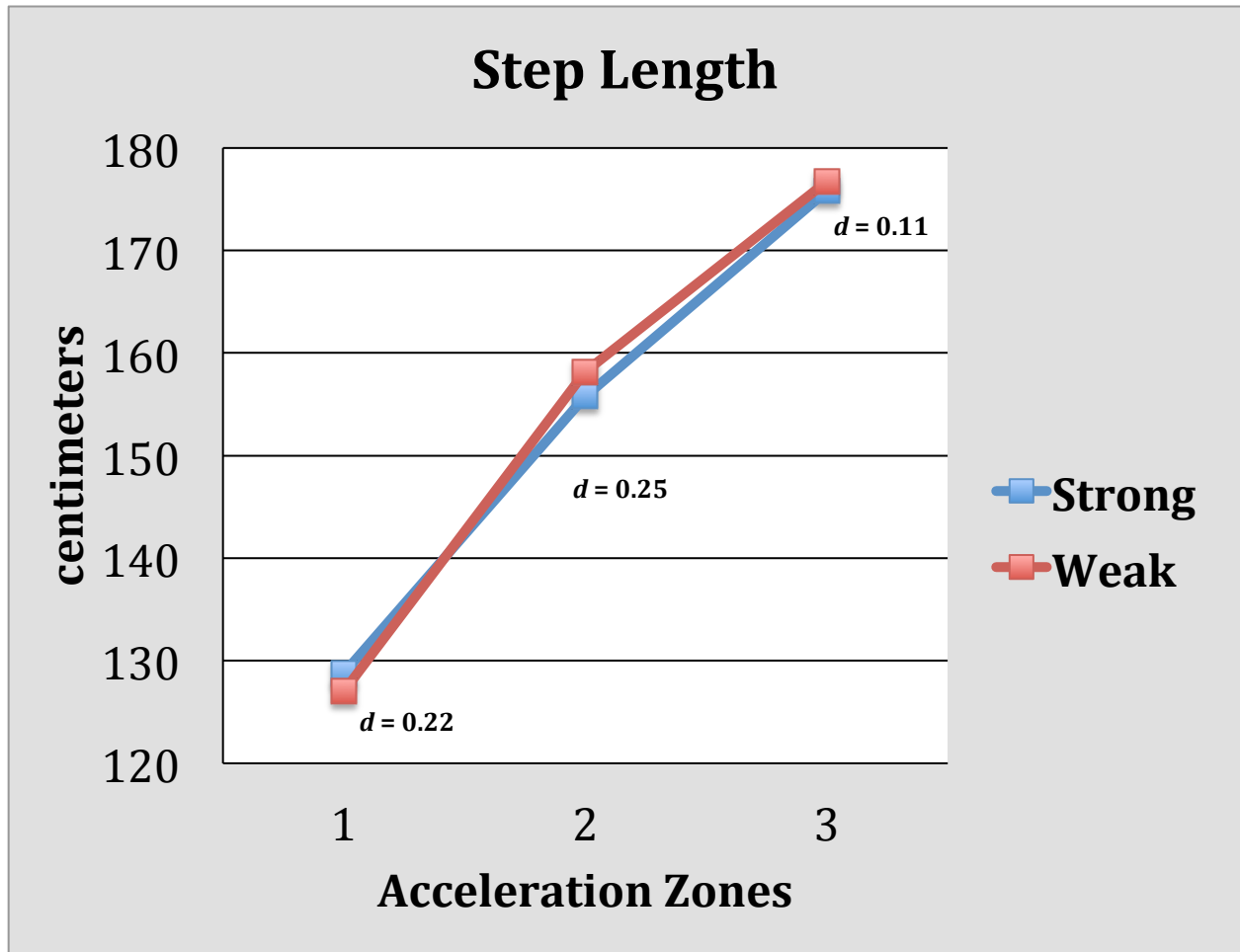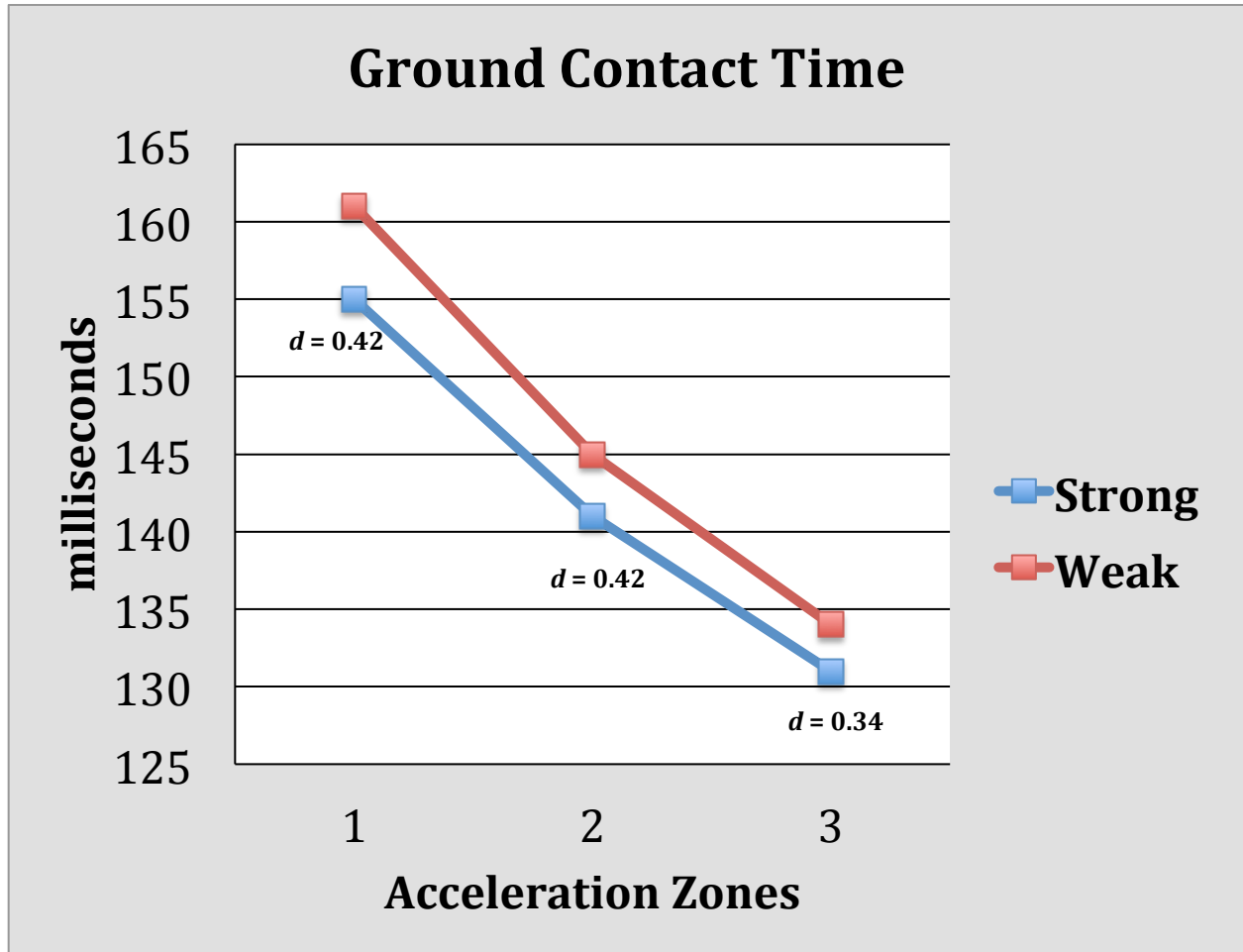*Table 5.5* Ground contact time difference between "strong" versus "weak" athletes

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Strong (ms)	155 ± 14	$146 - 164$	141 ± 11	$134 - 147$	131 ± 12	$126 - 137$
Weak (ms)	161 ± 14	$151 - 171$	145 ± 8	$138 - 152$	134 ± 4	$128 - 141$

Table 5.6 Differences in sprint characteristics between acceleration zones (N = 21)

Sprint Characteristic	Zone 1	Zone 2	Zone 3
Sprint Velocity (m/sec)	5.53 ± 0.26	6.99 ± 0.27**	8.00 ± 0.27*
Stride Length (cm)	127.93 ± 7.93	156.93 ± 9.62**	176.24 ± 8.37*
Stride Frequency (steps/sec)	4.34 ± 0.31	4.47 ± 0.28**	4.55 ± 0.24*
Ground Contact Time (ms)	158.09 ± 14.19	142.71 ± 10.01†	132.86 ± 9.32***

* = Statistically greater than zones 1 and 2 ($p = 0.000$), ** = Statistically greater than zone 1 ($p = 0.000$), *** = Statistically shorter than zones 1 and 2 ($p = 0.000$), † = Statistically shorter than zone 1 ($p = 0.000$)

"Higher Power" versus "Lower Power" Comparison

An independent samples t-test revealed the difference in SJ PPr 0kg between the higher

power and lower power groups to be statistically significant (t_{19} = 5.343, p = 0.000). Descriptive

data for both groups can be found in Table 5.7. All sprint variables were found to be within an

acceptable range of reliability for both the higher power and lower power groups with ICC

values of 0.85 – 0.98 and .89 – .98, respectively. CV values also ranged between 1.71 – 3.75%

and 0.87 – 3.49% for the higher power and lower power groups, respectively. SJ PPr 0kg was

also found to be reliable within the higher power and lower power groups with each exhibiting

ICC values of 0.95 and 0.96, respectively. CV values were also found to be reliable at 2.45% and

2.77% for the higher and lower power groups, respectively. Statistically significant main effects

for acceleration zone existed for SV ($F_{2,38}$ = 652.18, p = 0.000, c = 1.000), SL ($F_{2,38}$ = 952.37, p

= 0.000, c = 1.000), SF ($F_{2,38}$ = 9.63, p = 0.000, c = 0.973), and GCT ($F_{2,38}$ = 100.24, p = 0.000,

c = 1.000). *Post Hoc a*nalysis revealed that SV, SL, and SF in acceleration zone 3 were

statistically greater than acceleration zones 2 and 1 (Table 5.6). Additionally, SV, SL, and SF at

acceleration zone 2 were also statistically greater than zone 1 (Table 5.6). In contrast, GCT in

acceleration zone 3 was statistically greater than acceleration zones 1 and 2. GCT in acceleration

zone 2 was also statistically shorter than zone 1 (Table 5.6). 95% confidence intervals for the

difference in SV, SL, SF, and GCT between each acceleration zone can be found in the Tables

5.12-5.15 in Appendix C, respectively. There were statistically significant main effects for SJ

PPrel 0kg between athletes for SV ($F_{1,19}$ = 5.735, p = 0.027, c = 0.623) and GCT ($F_{1,19}$ = 4.792, p

= 0.041, c = 0.547), but not SL ($F_{1,19}$ = 0.758, p = 0.953, c = 0.050) or SF ($F_{1,19}$ = 1.661, p =

.213, c = 0.232). *Post Hoc* analysis revealed that the higher power group achieved statistically

greater SV in acceleration zones 2 (p = 0.040, 95% CI = 0.127– 0.468m/sec) and 3 (p = 0.041,

95% CI = 0.10 – 0.461m/sec) in comparison to the lower power group. Further *Post Hoc* analysis

revealed that the higher power group also displayed shorter GCT in acceleration zone 2 (p =

0.026, 95% CI = 1.26 – 17.70ms) compared to the lower power group as well.

Table 5.7 Descriptive data for the "higher power" and "lower power" groups

Variable	Mean	SD	95% CI Lower Bound	95% CI Upper Bound
Higher Power (W/kg)	59.85	1.48	58.93	60.77
Lower Power (W/kg)	50.30	1.35	49.46	51.13

Figure 5.8 Sprint velocity differences between athletes displaying "higher power" outputs versus "lower power" outputs
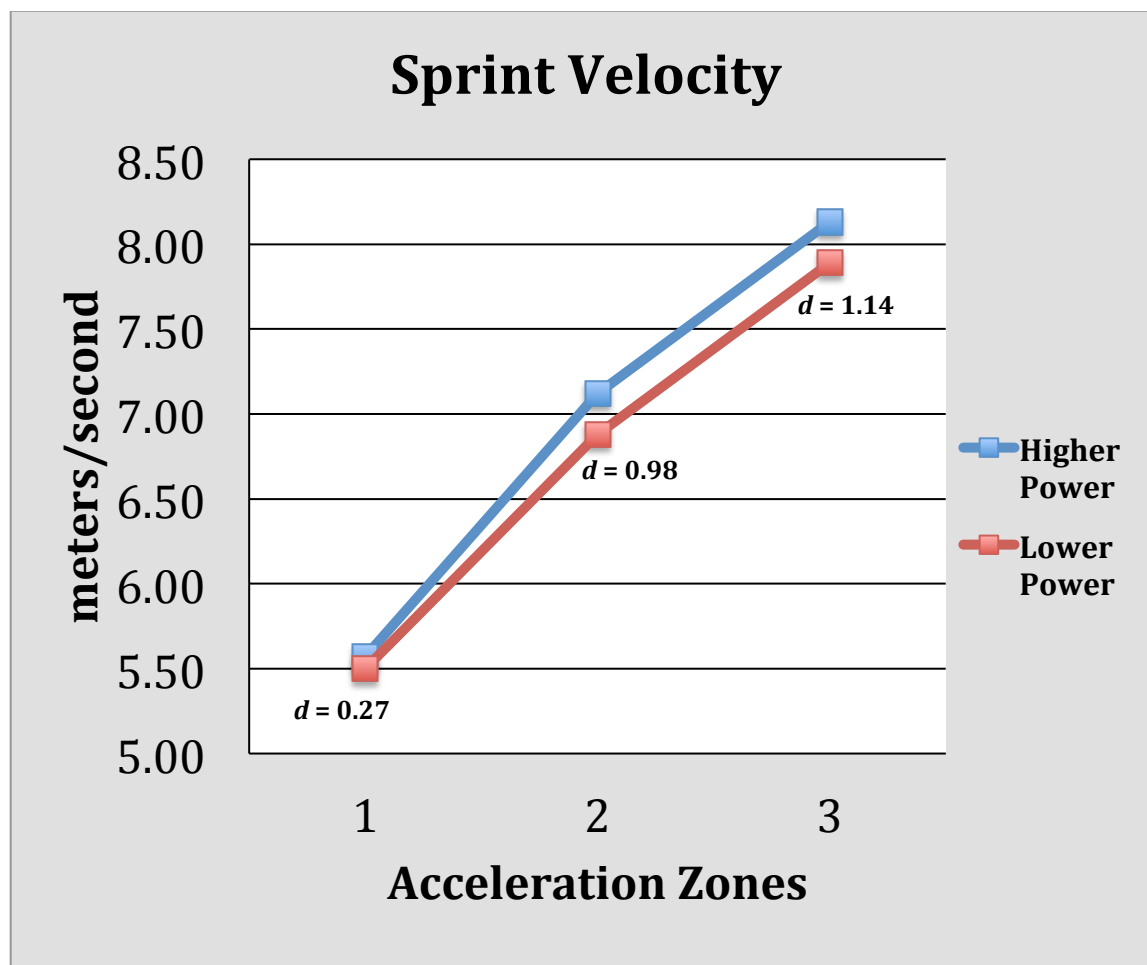
Table 5.8 Sprint velocity differences between athletes displaying "higher power" outputs versus "lower power" outputs

Group	Zone 1	95% CI	Zone 2	95% CI	Zone 3	95% CI
Higher Power	5.57 ± 0.21	$5.40 - 5.74$	7.12 ± 0.25*	$6.95 - 7.28$	8.13 ± 0.21*	$7.97 - 8.29$
Lower Power	5.5 ± 0.30	$5.34 - 5.66$	6.88 ± 0.24	$6.72 - 7.03$	7.89 ± 0.21	$7.74 - 8.05$

Note: * = statistically significant at the $p < 0.05$ level.

Figure 5.9 Step length differences between athletes displaying "higher power" outputs versus "lower power" outputs
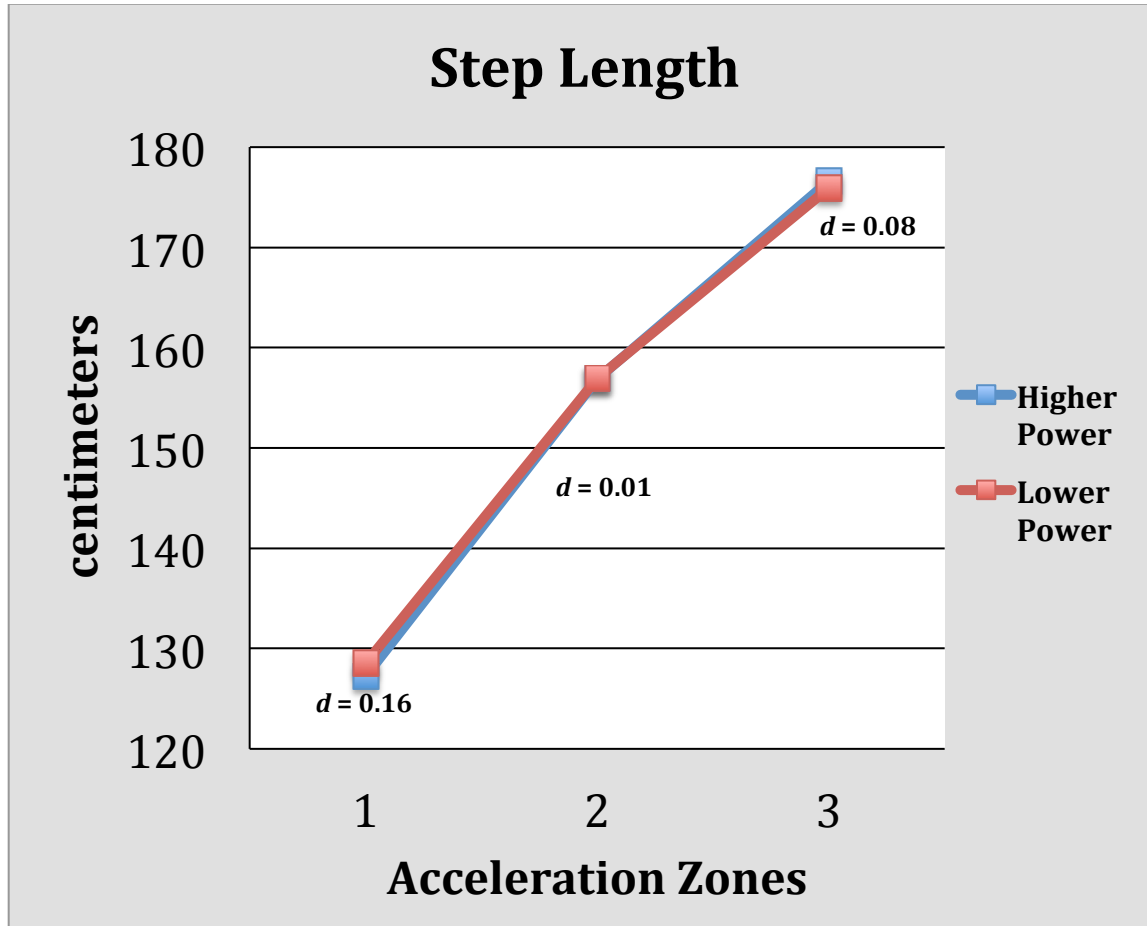
Table 5.9 Step length differences between athletes displaying "higher power" outputs versus "lower power" outputs

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Higher Power	127.25 ± 8.40	121.89 - 132.61	156.9 ± 10.88	150.37 – 163.43	176.6 ± 9.91	170.36 – 181.18
Lower Power	128.55 ± 7.82	123.43 - 133.66	156.96 ± 8.86	150.73 – 163.18	175.91 ± 7.17	170.50 – 182.28

Figure 5.10 Step frequency differences between athletes displaying "higher power" outputs versus "lower power" outputs
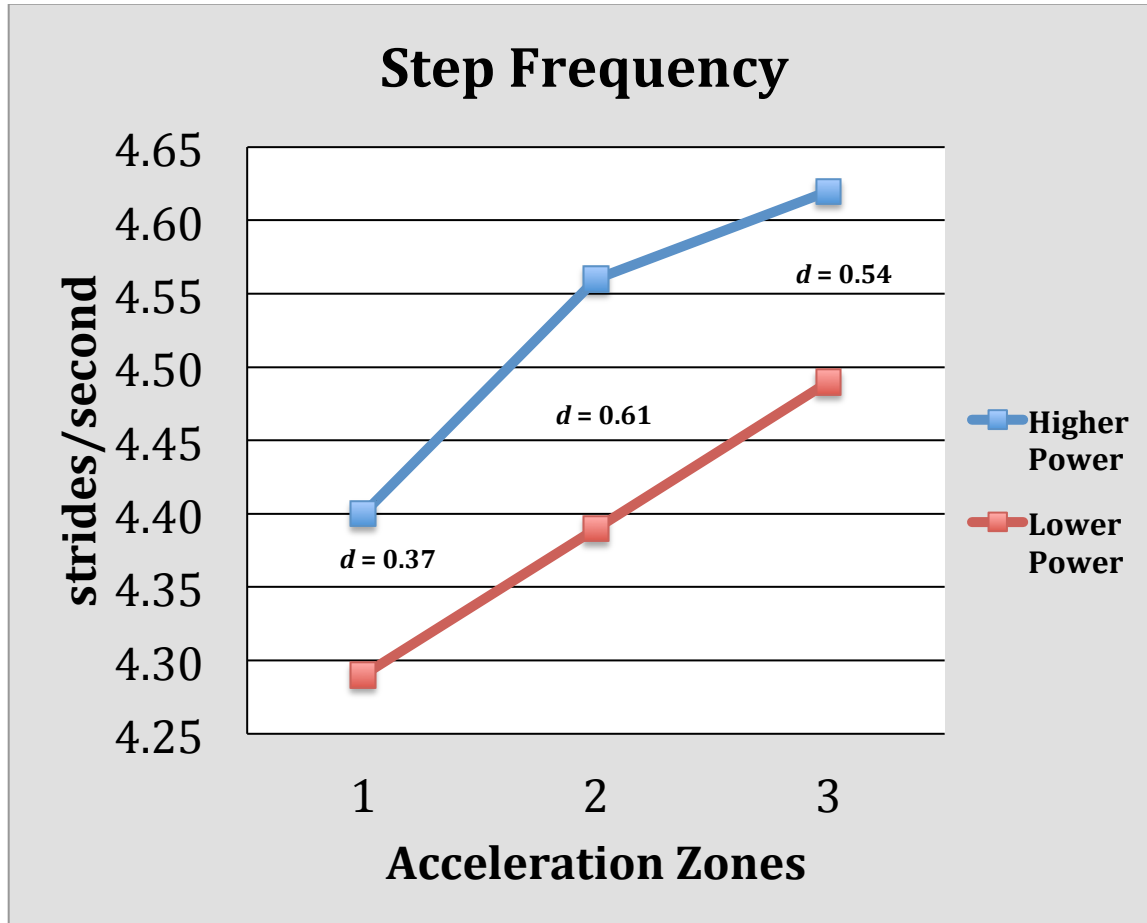
Table 5.10 Step frequency differences between athletes displaying "higher power" outputs versus "lower power" outputs

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Higher Power	4.40 ± 0.39	$4.19 - 4.61$	4.56 ± 0.34	$4.38 - 4.74$	4.62 ± 0.26	$4.47 - 4.77$
Lower Power	4.29 ± 0.39	$4.09 - 4.49$	4.39 ± 0.19	$4.21 - 4.56$	4.49 ± 0.21	$4.35 - 4.64$

Figure 5.11 Ground contact time differences between athletes displaying "higher power" outputs versus "lower power"
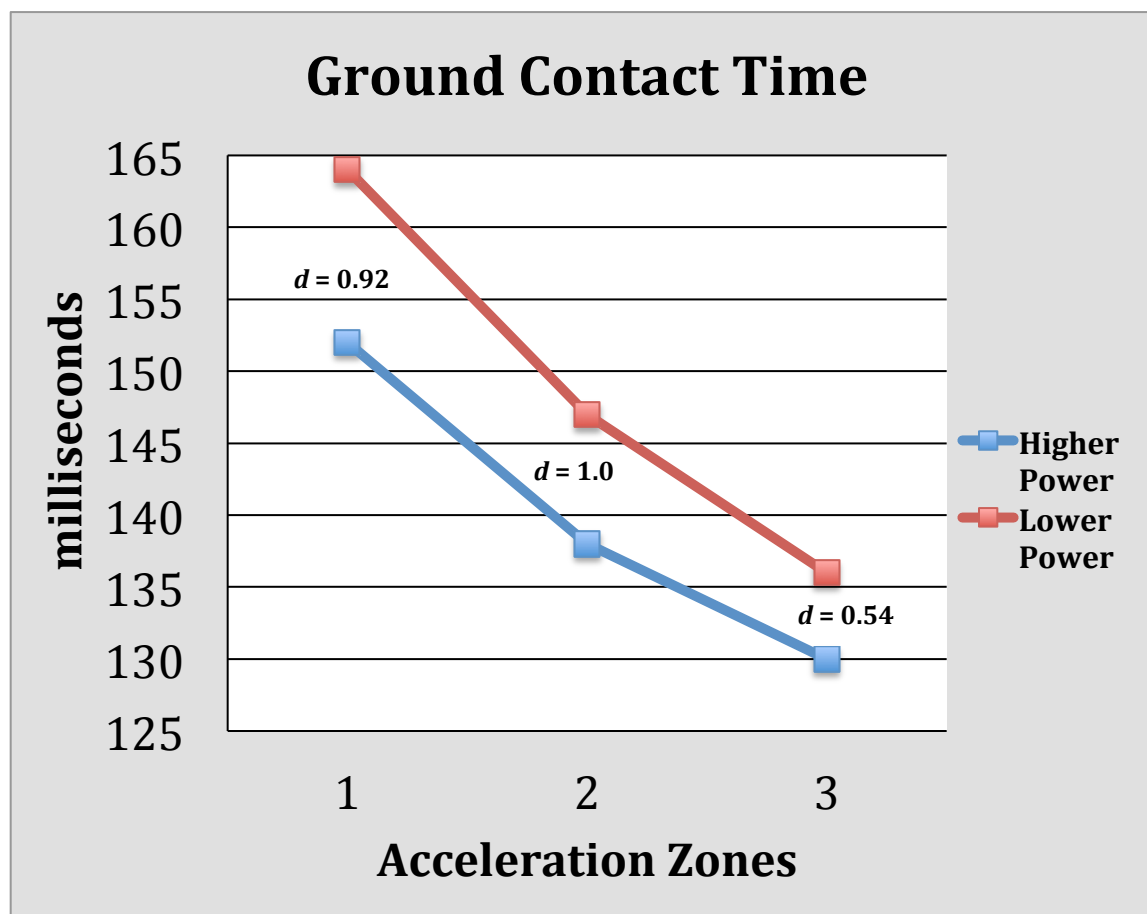
Table 5.11 Ground contact time differences between athletes displaying "higher power" outputs versus "lower power" outputs

Group	Zone 1	95% Confidence Interval	Zone 2	95% Confidence Interval	Zone 3	95% Confidence Interval
Strong	152 ± 11.86	$143 - 161$	138 ± 8.89*	$132 - 144$	130 ± 10.62	$124 - 135$
Weak	164 ± 14.44	$155 - 172$	147 ± 9.07	$142 - 153$	135 ± 7.11	$130 - 142$

Note: * = statistically significant at the $p < 0.05$ level.

DISCUSSION

The primary purposes of this investigation were twofold. First, this study aimed to compare the sprint characteristics in strong versus weak Division I men's collegiate soccer players during early-, mid-, and late-acceleration. Similarly, the second purpose of this study was to compare the same sprint metrics in athletes who display higher power outputs versus lower power outputs. The investigators hypothesized that the stronger and higher power output groups would achieve greater SV by displaying greater SF and shorter GCT in comparison to the weak and lower power output groups, respectively. The main findings of this study supported this hypothesis, as the stronger and higher power groups did in fact show these trends in comparison to their weak and lower power counterparts, respectively. Additionally, the differences in SV between these groups increased in magnitude at greater sprint distances. This appears to be catalyzed by rapid increases in SF between the early- and mid-acceleration zones for both the strong and high power cohorts (Figures 5.6 and 5.10). This trend may also be the result of the strong and higher power groups displaying consistently lower GCT across all three sub-sections of acceleration in comparison to the weak and lower power athletes (Figures 5.7 and 5.11).

Although statistically significant strength and power level main effects were sparse for these variables, the practical significance revealed by effect sizes accentuates the importance of these spatiotemporal characteristics. While some of these effects may be characterized as "small", they may be quite meaningful to performance. For example, the small-to-moderate effects for both SF ($d = .54 - .61$) and GCT ($d = .54 - 1.0$) may account for the statistically greater SV in zones 2 and 3 displayed by the higher power group, as SL ($d = 0.01 - 0.08$) only showed trivial effect sizes within these segments. Similar practical effects were also found in the

comparison between the strong and weak groups as well. Accordingly, these small-to-moderate effect sizes may have a significant impact on acceleration performance.

These results are in accordance with a host of other studies and reviews that have shown athletes who possess greater levels of MS (9, 13, 36, 41) and PP (1, 12, 13, 42) likely display superior sprint acceleration. Moreover, these findings are also in agreement with a number of previous investigations that have suggested faster FSA likely exhibit enhanced acceleration ability through increased SF and diminished GCT, but not SL (4, 27, 30, 38). For instance, Murphy et al. (38) found that "faster" FSA expressed greater SF and abbreviated GCT over the first three steps of a 15m sprint in comparison to "slower" FSA. Hewit et al. (27) also found faster national-level netball players to display greater SF over a distance of 2.5m in comparison to slower players. Most notably, however, a recent study by Bellon (4) found SF during the mid-acceleration zone to display moderate-to-strong, positive correlations with SJ PP 0kg, RFD@90, RFD@200, and RFD@250 in Division I men's soccer players. The investigators of that study also found GCT to exhibit moderate-to-strong, negative correlations with SJ PP 0kg and RFD at 90ms during all three sub-sections of acceleration as well. Considering the interrelationship between PP and RFD (48), the findings of the current study in combination with that of Bellon (4) support the notion that FSA who can quickly express high forces are more likely to possess greater acceleration ability in comparison to their less-powerful counterparts.

In contrast to these findings, however, the results of the current study conflict with others that have shown stronger relationships between sprint acceleration and SL, rather than SF, in FSA (31, 32). For example, Lockie and colleagues (31) found sprint acceleration over a distance of 5-10m to show moderate-to-strong correlations with both SL and GCT, but not SF. However, as noted by the authors, the faster athletes in this study (31) were likely able to express these

sprint characteristics by producing greater vertical GRF at a higher rate during ground contact. Therefore, despite expressing longer SL instead of higher SF, it appears the underlying mechanisms of those spatiotemporal variables are likely similar to those suggested in the current study. Opposing results were also found in another investigation by Lockie and colleagues (32), who examined the effect of different speed development protocols on 5-10m sprint performance in FSA over a 6-week period. The athletes were separated into groups performing free-sprint training, resisted sprint training, plyometric training, or resistance training. Interestingly, despite not having any sprint training over the 6-week period, the athletes in the resistance training group displayed the greatest practical effects from pre-to-post-testing in both 5 and 10m sprints, which appeared to result from increases in SL. Similar to the Lockie et al. (31), the investigators again noted that these augmentations to sprint mechanics were likely a reflection of increased power outputs, which were evident when examining the athletes' pre-to-posttest scores in a 5-bound protocol. While the sprint characteristics employed to reach greater SV may vary from one population to the next, a commonality in the literature appears to be that faster athletes produce force more efficiently, likely due to a superior RFD.

When considered from a training perspective, these results emphasize the concept that sprint acceleration is likely built upon a foundation of MS, as stronger athletes have been shown to display greater levels of PP (10, 44, 45, 47) and RFD (3, 25, 29, 43, 47). Consequently, the development of this fitness quality is of the upmost importance to improving acceleration performance. Additionally, due to the importance of power-related variables, such as PP and RFD (4), addressing the "force" and "velocity" ends of the force-velocity curve is also a key training consideration (1, 24, 47). These objectives can be met by integrating a "mixed-

methods" training approach (24, 39, 47) within the frameworks of block periodization and phase potentiation (15, 16).

Furthermore, properly integrating speed development tactics into these paradigms may also be warranted to not only compliment strength training adaptations, but also to maximize the transfer of training effect. Specifically, utilizing appropriate speed enhancement methods within the training process may allow athletes to learn how to effectively express higher force outputs during acceleration (5), as resistance training adaptations have shown to alter movement patterns and, subsequently, sport performance (10). The results of the current study are a prime example of this concept, as the strong and higher power groups, despite having no formal sprint training, displayed different acceleration characteristics in comparison to the weak and lower power groups. Consequently, the methodical implementation of speed, strength, and power development strategies within the training process is likely a critical component when aiming to bolster sprint acceleration. An amalgamation of these training factors into a single framework, known as Seamless Sequential Integration (SSI), has been proposed by DeWeese and colleagues (17, 18). Specifically, SSI merges block periodization, conjugate-sequential sequencing, and short-to-long speed development practices to improve sprint performance (17, 18). However, this particular model was implemented in a population of elite level bobsled athletes rather than FSA. To address this issue, an adapted model of SSI for men's soccer players was proposed by Bellon (4). Unfortunately, that model has not yet been investigated. Consequently, future studies should explore the longitudinal effects of that methodology on the development of sprint acceleration in men's soccer players.

PRACTICAL APPLICATION

The results of this study indicate that stronger, more-powerful Division I men's soccer players achieve greater SV by during acceleration by expressing greater SF due to shorter GCT. Practitioners and athletes should aim to develop MS, PP, and RFD by utilizing a mixed-methods training approach within the confines of block periodization and phase potentiation (15, 16). Additionally, SSI may also be used to integrate speed development methods into the training process in a logical and progressive manner (17, 18).

References

1. Baker D, Nance, S. The relation between running speed and measures of strength and power in professional rugby league players. *J Strength Cond Res* 13: 230-235, 1999.
2. Barr M. A series of studies examining the development of sprint speed and momentum of international rugby union players, in: *School of Exercise and Health Sciences*. Edith Cowan University, 2014.
3. Beckham G, Mizuguchi S, Carter C, Sato K, Ramsey M, Lamont H, Hornsby G, Haff G, and Stone M. Relationships of isometric mid-thigh pull variables to weightlifting performance. *J Sports Med Phys Fitness* 53: 573-581, 2013.
4. Bellon CR. The relationship between strength, power, and sprint acceleration in field sport athletes in: *Exercise and Sport Science*. East Tennessee State University, 2016.
5. Bobbert MF and Van Soest AJ. Effects of muscle strengthening on vertical jump height: a simulation study. *Med Sci Sports Exerc* 26: 1012-1020, 1994.
6. Brechue WF, Mayhew JL, and Piper FC. Characteristics of sprint performance in college football players. *J Strength Cond Res* 24: 1169-1178, 2010.
7. Carlock JM, Smith SL, Hartman MJ, Morris RT, Ciroslan DA, Pierce KC, Newton RU, Harman EA, Sands WA, and Stone MH. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *J Strength Cond Res* 18: 534-539, 2004.
8. Cometti G, Maffiuletti NA, Pousson M, Chatard JC, and Maffulli N. Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int J Sports Med* 22: 45-51, 2001.
9. Comfort P, Bullock N, and Pearson SJ. A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *J Strength Cond Res* 26: 937-940, 2012.
10. Cormie P, McGuigan MR, and Newton RU. Influence of strength on magnitude and mechanisms of adaptation to power training. *Med Sci Sports Exerc* 42: 1566-1581, 2010.
11. Cronin J, Hansen, K. Resisted sprint training for the acceleration phase of sprinting. *Strength & conditioning Journal* 28, 2006.
12. Cronin JB and Hansen KT. Strength and power predictors of sports speed. *J Strength Cond Res* 19: 349-357, 2005.
13. Cunningham DJ, West DJ, Owen NJ, Shearer DA, Finn CV, Bracken RM, Crewther BT, Scott P, Cook CJ, and Kilduff LP. Strength and power predictors of sprinting performance in professional rugby players. *J Sports Med Phys Fitness* 53: 105-111, 2013.
14. Delecluse C. Influence of strength training on sprint running performance. Current findings and implications for training. *Sports Med* 24: 147-156, 1997.
15. DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part 2: Practical and applied aspects. *Journal of sport and health science* 4: 318-324, 2015.
16. DeWeese BH, Hornsby G, Stone M, and Stone MH. The training process: Planning for strength-power training in track and field. Part I: Theoretical aspects. *Journal of sport and health science* 4: 308-317, 2015.
17. DeWeese BH, Sams ML, and Serrano AJ. Sliding toward Sochi–part1: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach* 1: 30-42, 2014.

18. DeWeese BH, Sams ML, and Serrano AJ. Sliding towards Sochi–part II: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach* 1: 4-7, 2014.

19. Faude O, Koch T, and Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci* 30: 625-631, 2012.

20. Ferro A, Villacieros J, Floria P, and Graupera JL. Analysis of speed performance in soccer by a playing position and a sports level using a laser system. *J Hum Kinet* 44: 143-153, 2014.

21. Gabbett T, Kelly J, Ralph S, and Driscoll D. Physiological and anthropometric characteristics of junior elite and sub-elite rugby league players, with special reference to starters and non-starters. *Journal of science and medicine in sport* 12: 215-222, 2009.

22. Gabbett TJ, Kelly JN, and Sheppard JM. Speed, change of direction speed, and reactive agility of rugby league players. *J Strength Cond Res* 22: 174-181, 2008.

23. Gissis I, Papadopoulos C, Kalapotharakos VI, Sotiropoulos A, Komsis G, and Manolopoulos E. Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Res Sports Med* 14: 205-214, 2006.

24. Haff G and Nimphius S. Training principles for power. *Strength & conditioning Journal* 34: 2-12, 2012.

25. Haff GG, Stone MH, O'Bryant HS, Harman EA, Dinan C, and Johnson R. Force-time dependent characteristics of dynamic and isometric muscle action *Journal of strength and conditioning research* 11: 269-272, 1997.

26. Haugen T, Tonnessen E, Hisdal J, and Seiler S. The role and development of sprinting speed in soccer. *Int J Sports Physiol Perform* 9: 432-441, 2014.

27. Hewit JK, Cronin JB, and Hume PA. Kinematic factors affecting fast and slow straight and change-of-direction acceleration times. *J Strength Cond Res* 27: 69-75, 2013.

28. http://sportsci.org/resource/stats/effectmag.html. Accessed January/2015.

29. Hornsby WG. A systematic approach to the monitoring of competitive weightlifters, in: *Exercise and Sport Science*. Johnson City, TN: East Tennessee State University, 2013.

30. Lockie RG, Murphy AJ, Knight TJ, and Janse de Jonge XA. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res* 25: 2704-2714, 2011.

31. Lockie RG, Murphy AJ, Schultz AB, Jeffriess MD, and Callaghan SJ. Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *J Strength Cond Res* 27: 2494-2503, 2013.

32. Lockie RG, Murphy AJ, Schultz AB, Knight TJ, and Janse de Jonge XA. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J Strength Cond Res* 26: 1539-1550, 2012.

33. Marques MC, Gil H, Ramos RJ, Costa AM, and Marinho DA. Relationships between vertical jump strength metrics and 5 meters sprint time. *J Hum Kinet* 29: 115-122, 2011.

34. Marques MC and Izquierdo M. Kinetic and kinematic associations between vertical jump performance and 10-m sprint time. *J Strength Cond Res* 28: 2366-2371, 2014.

35. Martinez-Valencia MA, Romero-Arenas S, Elvira JL, Gonzalez-Rave JM, Navarro-Valdivielso F, and Alcaraz PE. Effects of Sled Towing on Peak Force, the Rate of Force Development and Sprint Performance During the Acceleration Phase. *J Hum Kinet* 46: 139-148, 2015.

36. McBride JM, Blow D, Kirby TJ, Haines TL, Dayne AM, and Triplett NT. Relationship between maximal squat strength and five, ten, and forty yard sprint times. *J Strength Cond Res* 23: 1633-1636, 2009.

37. Meir R, Colla P, and Milligan C. Impact of the 10-metre rule change on professional rugby league: Implications for training. *Strength & conditioning Journal* 23: 42-46, 2001.

38. Murphy AJ, Lockie RG, and Coutts AJ. Kinematic determinants of early acceleration in field sport athletes. *J Sports Sci Med* 2: 144-150, 2003.

39. Newton RU and Kraemer WJ. Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength & conditioning Journal* 16: 20-31, 1994.

40. Rienzi E, Drust B, Reilly T, Carter JE, and Martin A. Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *J Sports Med Phys Fitness* 40: 162-169, 2000.

41. Seitz LB, Reyes A, Tran TT, Saez de Villarreal E, and Haff GG. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports Med* 44: 1693-1702, 2014.

42. Sleivert G and Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. *Eur J Appl Physiol* 91: 46-52, 2004.

43. Sole CJ. Analysis of countermovement jump force-time curve phase characteristics in athletes, in: *Exercise and Sport Science*. Johnson City, TN: East Tennessee State University, 2015.

44. Stone MH, Moir, G., Glaister, M., Sanders, R. How much strength is necessary? *Phys Ther Sport* 3: 88-96, 2002.

45. Stone MH, O'Bryant HS, McCoy L, Coglianese R, Lehmkuhl M, and Schilling B. Power and maximum strength relationships during performance of dynamic and static weighted jumps. *J Strength Cond Res* 17: 140-147, 2003.

46. Stone MH, Sands WA, Pierce KC, Carlock J, Cardinale M, and Newton RU. Relationship of maximum strength to weightlifting performance. *Med Sci Sports Exerc* 37: 1037-1043, 2005.

47. Stone MH, Stone, M., Sands, W. A. *Principles and Practice of Strength Training*. Champaign, IL: Human Kinetics, 2007.

48. Taber C, Bellon CR, Abbott H, and Bingham GE. Roles of maximal strength and rate of force development in maximizing muscular power. *Strength & conditioning Journal* 38: 71-78, 2016.

49. Thomas C, Comfort P, Chiang C-Y, and Jones PA. Relationship between isometric mid-thigh pull variables and sprint change of direction in collegiate athletes. *Journal of trainology* 4: 6-10, 2015.

50. Wang R, Hoffman JR, Tanigawa S, Miramonti AA, La Monica MB, Beyer KS, Church DD, Fukuda DH, and Jeffrey SR. Isometric Mid-Thigh Pull Correlates with Strength, Sprint and Agility Performance in Collegiate Rugby Union Players. *J Strength Cond Res*, 2016.

CHAPTER 6

SUMMARY AND FUTURE INVESTIGATIONS

The overall purpose of this dissertation was to develop a S2L model for FSA to more effectively integrate speed and strength development practices into the training process. In order to achieve this purpose, the following were explored as individual research investigations: 1.) an examination of the approximate distances constituting the early, mid, and late sub-phases of sprint acceleration in a population of Division I men's collegiate soccer players, 2.) an investigation of the relationships between various strength-power variables and key sprint characteristics during early-, mid-, and late-acceleration in a population of Division I men's soccer players, and 3.) a comparison of the spatiotemporal characteristics of "strong" versus "weak" and "more powerful" versus "less powerful" Division I men's soccer players during early-, mid-, and late- acceleration. By fulfilling these objectives, practitioners and athletes may benefit from understanding how to seamlessly integrate speed, strength, and power development practices into the training process for this athlete population.

The results of study I indicated that the early-, mid-, and late-acceleration zones may be characterized as approximately 0-2.5, 2.5-6, and 6-12m, respectively. When these sub-sections are considered within the context of the training process, they can be implemented in a manner similar to that described by DeWeese and colleagues (2014a, 2014b) using SSI. More specifically, BP can be used to merge the development of the early-, mid-, and late-acceleration sub-phases with that of SE, MS, and RFD, respectively. By coupling each segment of acceleration with these particular fitness characteristics, practitioners may utilize CSS to deliver unidirectional stimuli, or "concentrated loads", to their athletes within each phase of training. For example, a concentrated load of resistance training practices used to develop SE typically

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requires each exercise to be performed at higher training volumes (e.g. – 3 sets of 10 repetitions) (DeWeese, Hornsby, et al., 2015a, 2015b). By keeping the set and rep scheme consistent for each lift, these exercises may elicit a similar, "unidirectional" physiological response. Accordingly, applying the same concept to speed development by selecting methods emphasizing the early-acceleration zone may also foster a unified adaptive response as well. Consequently, the adaptations resulting from these concentrated loads may be superior in comparison to those garnered from multi-directional loading schemes (Stone, Stone, & Sands, 2007; Verkhoshansky, 1985).

More importantly, however, the effects resulting from a concentrated load of early-acceleration drills may act synergistically with those derived from resistance training. Specifically, the elevated resistance training volumes needed to establish a foundation of SE will likely limit an athlete's capacity to adapt to greater workloads in other areas of training, such as speed development, as these larger volume loads are typically accompanied by greater levels of fatigue (Sams, 2014), reduced force outputs (Flanagan et al., 2012; Marshall et al., 2011), and diminished motor control (Barker et al., 1990). Therefore, implementing longer sprint efforts may further inflate the athlete's volume load and potentially blunt strength development by activating catabolic mechanisms, such as PGC-1 alpha and AMPk (Smiles, Hawley, & Camera, 2016). In contrast, utilizing a concentrated load of shorter distance drills, particularly those pertinent to the early-acceleration segment, may aid the up-regulation of the mTOR pathway, while mitigating excessive phosphorylation of AMPk (Nader, 2006). From a physiological perspective, this is significant in that greater phosphorylation of mTOR, particularly mTORC1, may lead to greater increases in muscle cross-sectional area (Egerman & Glass, 2014; West, Burd, Staples, & Phillips, 2010), which could serve as the foundation for greater strength and

power improvements in subsequent training phases (Minetti, 2002; Zamparo, Minetti, & di Prampero, 2002). Furthermore, as the resistance training focus transitions towards enhancing MS and RFD, in accordance with the BP paradigm, training volume is typically lowered (i.e. – 3 sets of 3-5 repetitions) to accommodate for higher training intensities (DeWeese, Hornsby, et al., 2015a, 2015b; Stone, Stone, & Sands, 2007). Additionally, this reduction in training volume may also facilitate greater recovery-adaptation, which could foster greater strength and power development as well (Stone, Stone, & Sands, 2007). As a result, the athletes may be more capable of generating the high GRF necessary to achieve greater SV. Keeping this in mind, concentrated loads geared toward the mid- and late-acceleration zones may be more appropriate when the strength profile of the athlete matures.

Although the sets and repetitions for each exercise can be used to direct the purpose of a concentrated load, another key programming consideration driving this model is exercise selection. Simply put, each exercise should be selected to elicit a desired response. An often overlooked detail, however, is that the appropriateness of each exercise will vary based on the physiological status of the athlete. For instance, referring back to the previous example, higher training volumes resulting from a concentrated load of SE will likely diminish PP (Sams, 2014) and RFD (Flanagan et al., 2012; Marshall et al., 2011). This may be significant from a sprinting perspective in that these requisite strength-power qualities may underpin sprint performance during early-acceleration. To accommodate for this issue, exercise selection would have to be adjusted to account for lower force outputs. Accordingly, identifying which of these strength-associates was most relevant to early-, mid-, and late-acceleration in study II was the next logical step in developing an integrated model for FSA.

The results of study II suggested that PP and RFD at earlier time-points (i.e. – RFD@90) appear to be related to producing shorter GCT during all sub-sections of acceleration, as well as SF during mid-acceleration. Additionally, PP and RFD at later time-points (i.e. – RFD@200 and RFD@250) were more related to increasing SF, particularly during mid-acceleration. Previous studies have suggested that faster team sport athletes express shorter GCT and greater SF during acceleration in comparison to their slower counterparts (Hewit, Cronin, & Hume, 2013; Lockie et al., 2011; Murphy, Lockie, & Coutts, 2003). Therefore, since PP and RFD are likely related to these critical sprint variables, higher training volumes may blunt the development of these abilities, thus hindering sprint performance. To address this issue, practitioners are encouraged to consider employing tactics that require inherently longer GCT when higher resistance training volumes are implemented.

While this may sound counterintuitive, one may hypothesize that methods such as sled towing and incline sprinting may require the athlete to generate a higher propulsive IP over a longer period of time (Gottschall & Kram, 2005), thus accommodating for lower RFD and PP. Furthermore, Spinks et al. (2007) showed that sled towing led to a greater anterior lead of the torso, particularly during the first two steps of acceleration, over the course of an 8-week training period in FSA. As Kugler and Janshen (2010) remind us, an athlete's body position greatly influences their ability to develop high propulsive forces, which may dictate the SV attained during acceleration. Additionally, Mann (2013) also suggests that the ability to maintain a greater anterior lean of the torso allows the athlete to accelerate for greater distances, potentially leading to greater SV. Accordingly, various forms of resisted sprinting may be warranted to supply a concentrated load during periods that require higher resistance training volumes.

Perhaps even more important, this tactic may allow the athlete to attain more advantageous body positions to accelerate greater distances in subsequent training phases.

With that said, it is also important to evaluate the training status and strength level of each athlete when determining the appropriateness of training methods as well. Recent evidence has shown that stronger athletes tend to display a superior ability to handle higher training loads, while weaker athletes appear to take longer to recover and adapt from greater training demands (Johnston, Gabbett, Jenkins, & Hulin, 2015; Sole, 2015). When revisiting the previous example of a block emphasizing early-acceleration and SE, weaker athletes may not be able to adapt beyond the workloads resulting from resistance training. Taking this information into account, when working with less-trained athletes, a "less is more" approach is likely warranted. Lockie and colleagues (2012) have even showed that resistance training alone over a period of 6-weeks was enough to improve the acceleration capacity in FSA. Therefore, coupling resistance training sessions with very conservative speed development practices is likely enough to improve acceleration ability for weaker athletes.

In contrast to this notion, stronger, more advanced athletes appear to display a diminished transfer of training effect with respect to sprinting in comparison to their less-trained cohorts (Barr et al., 2014). As noted by Barr and colleagues (2014), this could indicate an exhaustion of the initial technique and neuromuscular adaptations that improve sprinting speed. This could also be due to the simple fact that these athletes are closer to their genetic potential, which may stifle their rate of adaptation. Furthermore, these individuals may benefit from implementing tasks that possess greater levels of specificity. As Siff (2009) reminds us, to successfully transfer to athletics performance, exercises must overload a host of parameters including the type of muscle action, the magnitude of force applied, as well as the RFD inherent to the task. Keeping this in

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mind, these individuals may show a more positive adaptive response to additional speed development tactics, such as sled towing, incline sprinting, or other sprint drills. Regardless of the strength level of the athlete, however, the physiological status of the athlete should be continuously monitored so that objective training decisions can be made. Despite the fact that stronger athletes appear to tolerate higher training loads with greater ease, the training and competitive demands inherent to sport still affect these athletes as well. As such, consistently assessing the fatigue level of each athlete may allow practitioners to better evaluate the appropriateness of each training method for his or her athletes.

While selecting suitable speed enhancement tactics is an important part in organizing the training process, the importance of establishing high-levels of MS, PP, and RFD cannot be overstated. The results of study III strongly support this notion. In particular, athletes designated to the "strong" and "higher power output" groups attained greater SV during acceleration by displaying greater SF and shorter GCT in comparison to the "weak" and "lower power output" groups. Although these results appear to conflict with other studies that have reported faster FSA to display superior SL, rather than SF, over abbreviated GCT (Lockie et al., 2013; Lockie et al., 2012), a commonality amongst all of these investigations appears to be the importance of PP. More specifically, regardless of which sprint characteristics were expressed to reach greater SV, each of these studies suggest that this result was likely due to the expression of higher power outputs. Also, the differences in spatiotemporal characteristics may have been attributed to varying athlete populations between investigations, as both studies that reported conflicting results included a wide variety of FSA such as soccer, rugby, and field hockey. Consequently, the positions from which athletes accelerate likely differ in each sport. For instance, field hockey players are often more flexed at the hip to control the ball and accelerate while holding a stick in

their hands, while rugby players are also likely to adopt different sprint characteristics when carrying a ball during gameplay (Barr, 2014). Taking these differences into consideration, sprint characteristics displayed by faster athletes do appear to differ between sport populations, but the expression of higher-levels of PP is probably a common underlying mechanism across all FSA.

Despite the obvious importance of this fitness characteristic, PP is likely a by-product of RFD via the impulse-momentum relationship (Taber et al., 2016). In other words, the higher RFD an athlete can express, the greater the IP generated, which, subsequently, enhances PP. Consequently, greater PP outputs may be a reflection of an improved ability to express higher rates of force. Regardless of which power-associate is the precise mechanism to enhancing acceleration, it is imperative to recall the relationship between both of these qualities and MS, as stronger athletes often possess higher PP (Cormie et al., 2010a; Stone, Moir, Glaister, & Sanders, 2002; Stone et al., 2003; Stone, Stone, & Sands, 2007) and RFD (Beckham et al., 2013; Haff et al., 1997; Hornsby, 2013; Sole, 2015; Stone, Stone, & Sands, 2007). Ultimately, establishing a solid foundation of MS may facilitate greater potential to express greater PP and RFD (Taber et al. 2016; Cormie et al., 2010a).

Interestingly, despite that MS (Comfort, Haigh, & Matthews, 2012; Cunningham et al., 2013; McBride et al., 2009; Seitz, Reyes, Tran, Saez de Villarreal, & Haff, 2014) and PP (Baker, 1999; Cronin & Hansen, 2005; Cunniffe et al., 2009; Sleivert & Taingahue, 2004) have been linked with acceleration performance in numerous studies and reviews, study III is perhaps the first to investigate the effects of these fitness qualities on sprint characteristics. The results of this study further validate the notion that the kinetic profile of an athlete may influence his or her movement mechanics. In addition, although a biomechanical analysis was not apart of this study, the differences in spatiotemporal profiles in strong versus weak and high power output versus

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low power output groups likely indicate different movement strategies employed during acceleration, which appears to be supported by a number of previous investigations (DeWeese, Sams, et al., 2015; Mann, 2013; Murphy et al., 2003; Weyand et al., 2010). For example, previous literature has indicated that faster athletes often display abbreviated knee angles prior to toe-off during acceleration (Mann, 2013; Murphy et al., 2003), which may lead to an earlier initiation of the recovery phase, or "swing time". Swing time constitutes the period over which the athlete repositions his or her legs between steps. According to Weyand et al. (2010), swing time is not statistically different between "fast" and "slow" runners. Therefore, faster athletes do not appear to reposition their legs at a faster rate, but rather find themselves in a more advantageous position to "attack the ground" by achieving greater hip flexion (DeWeese, Sams, et al., 2015; Mann, 2013), potentially contacting the ground in closer proximity to their center of mass (Mero, Komi, & Gregor, 1992). This mechanical advantage may lead to enhanced RFD during the stance phase, higher GRF, and greater SV. Overall, it can be surmised that producing higher forces during acceleration likely allows the athlete to attain sprint mechanics that afford him or her to continue to generate higher GRF at greater distances, thus potentiating top-end speed. Ultimately, sprint speed is built upon a foundation of MS (DeWeese, Sams, et al., 2015).

While this adapted version of SSI is an evidence-based model, only a theoretical foundation for this framework has been provided in this dissertation. Future investigations should aim to test the efficacy of this paradigm across athletes of different sports and strength levels through the use of sound athlete monitoring practices. Additionally, although higher-level players appear to be faster accelerators from a static position (Ferro et al., 2014; Gabbett et al., 2009; Gabbett et al., 2008; Gissis et al., 2006), it is still unknown if these athletes are also faster when initiating a sprint effort from a walk, jog, or run. Subsequently, follow-up investigations

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should also examine the relationship between acceleration ability from a static position and the re-acquisition of acceleration while "on the move". Lastly, future research should also aim to further investigate the efficacy of particular speed development methods, such as sled towing and incline sprinting. By fostering a better understanding of the longitudinal training effects derived from these tactics, they may be implemented with greater purpose at particular times of the training year.

In conclusion, this model of SSI for FSA is not intended to be used a rigid structure to organize the training process. Rather, it is a conceptual framework that can be adapted to fit the training demands of each athlete in a variety of scenarios. Due to the variable demands of different sports, positions, and playing styles, a "one-size fits all" model is unrealistic and impractical. Simply put, no theoretical paradigm can replace a sound understanding of the training process, the physiological theory governing adaptation, and common sense. As such, practitioners are encouraged to tailor the theoretical concepts provided in this dissertation to meet the practical needs of their athletes.

REFERENCES

Aagaard, P. (2003). Training-induced changes in neural function. *Exercise and sport sciences reviews, 31*(2), 61-67.

Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol (1985), 93*(4), 1318-1326. doi: 10.1152/japplphysiol.00283.2002

Adams, G. R., Hather, B. M., Baldwin, K. M., & Dudley, G. A. (1993). Skeletal muscle myosin heavy chain composition and resistance training. *J Appl Physiol (1985), 74*(2), 911-915.

Alexander, M. J. (1989). The relationship between muscle strength and sprint kinematics in elite sprinters. *Canadian journal of sport sciences = Journal canadien des sciences du sport, 14*(3), 148-157.

Allen, D. L., Roy, R. R., & Edgerton, V. R. (1999). Myonuclear domains in muscle adaptation and disease. *Muscle Nerve, 22*(10), 1350-1360.

Almeida-Silveira, M. I., Perot, C., Pousson, M., & Goubel, F. (1994). Effects of stretch-shortening cycle training on mechanical properties and fibre type transition in the rat soleus muscle. *Pflugers Arch, 427*(3-4), 289-294.

Andersen, L. L., & Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European journal of applied physiology, 96*(1), 46-52. doi: 10.1007/s00421-005-0070-z

Baker, D. (2001a). Comparison of upper-body strength and power between professional and college-aged rugby league players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 15*(1), 30-35.

Baker, D. (2001b). A series of studies on the training of high-intensity muscle power in rugby league football players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 15*(2), 198-209.

Baker, D., Nance, S. (1999). The relation between running speed and measures of strength and power in professional rugby league players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 13*, 230-235.

Bangsbo, J., Norregaard, L., & Thorso, F. (1991). Activity profile of competition soccer. *Canadian journal of sport sciences = Journal canadien des sciences du sport, 16*(2), 110-116.

Barker, M., Poe, C., Midgett, V., O'Bryant, H. S., Stone, M. H., Warren, B., . . . Johnson, R. (1990). *Performance response to short-term overwork in elite junior olympic weightlifters.* Paper presented at the Carolinas Biomechanics Symposium, Greenville, NC.

Barr, M. (2014). *A series of studies examining the development of sprint speed and momentum of international rugby union players.* (Doctor of Philosophy), Edith Cowan University.

Barr, M. J., Sheppard, J. M., & Newton, R. U. (2013). Sprinting kinematics of elite rugby players. *Journal of austrailian strength and conditioning, 21*(4), 14-20.

Barr, M. J., Sheppard, J. M., Agar-Newman, D. J., & Newton, R. U. (2014). Transfer effect of strength and power training to the sprinting kinematics of international rugby players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 28*(9), 2585-2596. doi: 10.1519/JSC.0000000000000423

Barr, M. J., Sheppard, J. M., Gabbett, T. J., & Newton, R. U. (2014). Long-term training-induced changes in sprinting speed and sprint momentum in elite rugby union players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 28*(10), 2724-2731. doi: 10.1519/JSC.0000000000000364

Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., . . . Stone, M. (2013). Relationships of isometric mid-thigh pull variables to weightlifting performance. *The Journal of sports medicine and physical fitness, 53*(5), 573-581.

Bellon, C. R. (2016). *The relationship between strength, power, and sprint acceleration in field sport athletes* (Doctor of Philosophy), East Tennessee State University.

Ben Abdelkrim, N., Castagna, C., Jabri, I., Battikh, T., El Fazaa, S., & El Ati, J. (2010). Activity profile and physiological requirements of junior elite basketball players in relation to aerobic-anaerobic fitness. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(9), 2330-2342. doi: 10.1519/JSC.0b013e3181e381c1

Bevan, H. R., Bunce, P. J., Owen, N. J., Bennett, M. A., Cook, C. J., Cunningham, D. J., . . . Kilduff, L. P. (2010). Optimal loading for the development of peak power output in professional rugby players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(1), 43-47. doi: 10.1519/JSC.0b013e3181c63c64

Bezodis, N. E. (2009). *Biomechanical investigations of sprint start technique and performance.* University of Bath.

Black, W., & Elmo, R. (1994). Comparisons of size, strength, speed, and power in NCAA division 1-A football players. *Journal of strength and conditioning research, 8*(2), 80-85.

Bobbert, M. F., & Van Soest, A. J. (1994). Effects of muscle strengthening on vertical jump height: a simulation study. *Medicine and science in sports and exercise, 26*(8), 1012-1020.

Bompa, T. O., & Haff, G. (2009). *Periodization: Theory and methodology of training* (5 ed.). Champaign, IL: Human Kinetics.

Bosco, C., Ito, A., Komi, P. V., Luhtanen, P., Rahkila, P., Rusko, H., & Viitasalo, J. T. (1982). Neuromuscular function and mechanical efficiency of human leg extensor muscles during jumping exercises. *Acta physiologica Scandinavica, 114*(4), 543-550. doi: 10.1111/j.1748-1716.1982.tb07022.x

Brechue, W. F., Mayhew, J. L., & Piper, F. C. (2010). Characteristics of sprint performance in college football players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(5), 1169-1178. doi: 10.1519/JSC.0b013e3181d68107

Bret, C., Rahmani, A., Dufour, A. B., Messonnier, L., & Lacour, J. R. (2002). Leg strength and stiffness as ability factors in 100 m sprint running. *The Journal of sports medicine and physical fitness, 42*(3), 274-281.

Bruggerman, G. P., & Glad, B. (1990). Time analysis of the sprint events. In G. P. Bruggemann & B. Glad (Eds.), *IAAF Scientific Research Project at the Games of the XXXIV Olympiad-Seoul 1998: Final Report* (pp. 10-45). Italy.

Brughelli, M., & Cronin, J. (2008). A review of research on the mechanical stiffness in running and jumping: methodology and implications. *Scand J Med Sci Sports, 18*(4), 417-426. doi: 10.1111/j.1600-0838.2008.00769.x

Buller, A. J., Eccles, J. C., & Eccles, R. M. (1960). Interactions between motoneurones and muscles in respect of the characteristic speeds of their responses. *The Journal of physiology, 150*, 417-439.

Cappadona, J. (2013). *Kinematic and spatiotemporal analysis between sprint drills and maximal sprinting.* Sacred Heart University, Fairfield University.

Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., . . . Stone, M. H. (2004). The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *Journal of strength and conditioning research / National Strength & Conditioning Association, 18*(3), 534-539. doi: 10.1519/R-13213.1

Chelly, S. M., & Denis, C. (2001). Leg power and hopping stiffness: relationship with sprint running performance. *Medicine and science in sports and exercise, 33*(2), 326-333.

Chen, J. R., Wang, T. J., Huang, L. J., Chen, L. J., Huang, Y. S., Wang, Y. J., & Tseng, G. F. (2009). Fatigue reversibly reduced cortical and hippocampal dendritic spines concurrent with compromise of motor endurance and spatial memory. *Neuroanatomy, 161*(4), 1104-1113.

Clark, K. P., & Weyand, P. G. (2014). Are running speeds maximized with simple-spring stance mechanics? *Journal of applied physiology, 117*(6), 604-615. doi: 10.1152/japplphysiol.00174.2014

Clark, K. P., Stearne, D. J., Walts, C. T., & Miller, A. D. (2010). The longitudinal effects of resisted sprint training using weighted sleds vs. weighted vests. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(12), 3287-3295. doi: 10.1519/JSC.0b013e3181b62c0a

Coh, M., Milanovic, D., & Kampmiller, T. (2001). Morphologic and kinematic characteristics of elite sprinters. *Coll Antropol, 25*(2), 605-610.

Coh, M., Tomazin, K. (2006). Kinematic analysis of the sprint start and acceleration from the blocks. *New studies in athletics, 21*(3), 23-33.

Cometti, G., Maffiuletti, N. A., Pousson, M., Chatard, J. C., & Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *International journal of sports medicine, 22*(1), 45-51. doi: 10.1055/s-2001-11331

Comfort, P., Bullock, N., & Pearson, S. J. (2012). A comparison of maximal squat strength and 5-, 10-, and 20-meter sprint times, in athletes and recreationally trained men. *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(4), 937-940. doi: 10.1519/JSC.0b013e31822e5889

Comfort, P., Haigh, A., & Matthews, M. J. (2012). Are changes in maximal squat strength during preseason training reflected in changes in sprint performance in rugby league players? *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(3), 772-776. doi: 10.1519/JSC.0b013e31822a5cbf

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010a). Influence of strength on magnitude and mechanisms of adaptation to power training. *Medicine and science in sports and exercise, 42*(8), 1566-1581. doi: 10.1249/MSS.0b013e3181cf818d

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010b). Adaptations in athletic performance after ballistic power versus strength training. *Medicine and science in sports and exercise, 42*(8), 1582-1598. doi: 10.1249/MSS.0b013e3181d2013a

Cormie, P., McGuigan, M. R., & Newton, R. U. (2010c). Changes in the eccentric phase contribute to improved stretch-shorten cycle performance after training. *Medicine and science in sports and exercise, 42*(9), 1731-1744. doi: 10.1249/MSS.0b013e3181d392e8

159

Cormie, P., McGuigan, M. R., & Newton, R. U. (2011). Developing maximal neuromuscular power: Part 1--biological basis of maximal power production. *Sports medicine, 41*(1), 17-38. doi: 10.2165/11537690-000000000-00000

Cornu, C., Almeida Silveira, M. I., & Goubel, F. (1997). Influence of plyometric training on the mechanical impedance of the human ankle joint. *European journal of applied physiology and occupational physiology, 76*(3), 282-288.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *Journal of strength and conditioning research / National Strength & Conditioning Association, 19*(2), 349-357. doi: 10.1519/14323.1

Cronin, J. & Hansen, K. (2006). Resisted sprint training for the acceleration phase of sprinting. *Strength & conditioning Journal, 28*(42-51).

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software. *Journal of strength and conditioning research / National Strength & Conditioning Association, 23*(4), 1195-1203. doi: 10.1519/JSC.0b013e3181a3928b

Cunniffe, B., Proctor, W., Baker, J. S., & Davies, B. (2009). An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software. *Journal of strength and conditioning research / National Strength & Conditioning Association, 23*(4), 1195-1203. doi: 10.1519/JSC.0b013e3181a3928b

Cunningham, D. J., West, D. J., Owen, N. J., Shearer, D. A., Finn, C. V., Bracken, R. M., . . . Kilduff, L. P. (2013). Strength and power predictors of sprinting performance in professional rugby players. *The Journal of sports medicine and physical fitness, 53*(2), 105-111.

Debaere, S., Delecluse, C., Aerenhouts, D., Hagman, F., & Jonkers, I. (2013). From block clearance to sprint running: characteristics underlying an effective transition. *Journal of sports sciences, 31*(2), 137-149. doi: 10.1080/02640414.2012.722225

Delecluse, C. (1997). Influence of strength training on sprint running performance. Current findings and implications for training. *Sports medicine, 24*(3), 147-156.

Deschenes, M. R., Judelson, D. A., Kraemer, W. J., Meskaitis, V. J., Volek, J. S., Nindl, B. C., . . . Deaver, D. R. (2000). Effects of resistance training on neuromuscular junction morphology. *Muscle Nerve, 23*(10), 1576-1581.

Desmedt, J. E., & Godaux, E. (1977). Ballistic contractions in man: characteristic recruitment pattern of single motor units of the tibialis anterior muscle. *The Journal of physiology, 264*(3), 673-693.

DeWeese, B. H. (2015). *Development of phase potentiation for strength and power athletes.* Paper presented at the NSCA Coaches Conference, Louisville, KY.

DeWeese, B. H., Bellon, C. R., Magrum, E., Taber, C., & Suchomel, T. J. (2016). Strengthening the springs: How the inclusion of properly sequenced weightlifting derivatives into the strength-training program can improve sprint performance. *Techniques in track & field and cross-country, 9*(3), 9-20.

DeWeese, B. H., Hornsby, G., Stone, M., & Stone, M. H. (2015a). The training process: Planning for strength-power training in track and field. Part 2: Practical and applied aspects. *Journal of sport and health science, 4*(4), 318-324.

DeWeese, B. H., Hornsby, G., Stone, M., & Stone, M. H. (2015b). The training process: Planning for strength-power training in track and field. Part I: Theoretical aspects. *Journal of sport and health science, 4*(4), 308-317.

DeWeese, B. H., Sams, M. L., & Serrano, A. J. (2014a). Sliding towards Sochi–part I: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach, 1*(3), 30-42.

DeWeese, B. H., Sams, M. L., & Serrano, A. J. (2014b). Sliding towards Sochi–part II: a review of programming tactics used during the 2010–2014 quadrennial. *Natl Strength Cond Assoc Coach, 1*(4), 4-7.

DeWeese, B. H., Sams, M. L., Williams, J. H., & Bellon, C. R. (2015). The nature of speed: Enhancing sprint abilities through a short to long training approach. *Techniques in Track & Field and Cross Country, 8,* 8-24.

Dodd, D. J., & Alvar, B. A. (2007). Analysis of acute explosive training modalities to improve lower-body power in baseball players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 21*(4), 1177-1182. doi: 10.1519/R-21306.1

Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units. *J Appl Physiol (1985), 101*(6), 1766-1775. doi: 10.1152/japplphysiol.00543.2006

Duthie, G. M., Pyne, D. B., Marsh, D. J., & Hooper, S. L. (2006). Sprint patterns in rugby union players during competition. *Journal of strength and conditioning research / National Strength & Conditioning Association, 20*(1), 208-214. doi: 10.1519/R-16784.1

Egerman, M. A., & Glass, D. J. (2014). Signaling pathways controlling skeletal muscle mass. *Crit Rev Biochem Mol Biol, 49*(1), 59-68. doi: 10.3109/10409238.2013.857291

Eniseler, N., Camliyer, H., & Gode, O. (1996). A comparison of 30-meter sprint values with respect to various leage levels and positions of the soccer players playing in these leagues. *J Soccer Sci Technol, 3*, 3-8.

Faigenbaum, A. D., McFarland, J. E., Keiper, F. B., Tevlin, W., Ratamess, N. A., Kang, J., & Hoffman, J. R. (2007). Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *Journal of sports science & medicine, 6*(4), 519-525.

Farlinger, C. M., Kruisselbrink, L. D., & Fowles, J. R. (2007). Relationships to skating performance in competitive hockey players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 21*(3), 915-922. doi: 10.1519/R-19155.1

Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of sports sciences, 30*(7), 625-631. doi: 10.1080/02640414.2012.665940

Ferro, A., Villacieros, J., Floria, P., & Graupera, J. L. (2014). Analysis of speed performance in soccer by a playing position and a sports level using a laser system. *Journal of human kinetics, 44*, 143-153. doi: 10.2478/hukin-2014-0120

Flanagan, S. D., Dunn-Lewis, C., Comstock, B. A., Maresh, C. M., Volek, J. S., Denegar, C. R., & Kraemer, W. J. (2012). Cortical Activity during a Highly-Trained Resistance Exercise Movement Emphasizing Force, Power or Volume. *Brain Sci, 2*(4), 649-666. doi: 10.3390/brainsci2040649

Ford, H. T., Jr., Puckett, J. R., Drummond, J. P., Sawyer, K., Gantt, K., & Fussell, C. (1983). Effects of three combinations of plyometric and weight training programs on selected physical fitness test items. *Percept Mot Skills, 56*(3), 919-922. doi: 10.2466/pms.1983.56.3.919

161

Foure, A., Nordez, A., & Cornu, C. (2010). Plyometric training effects on Achilles tendon stiffness and dissipative properties. *J Appl Physiol (1985), 109*(3), 849-854. doi: 10.1152/japplphysiol.01150.2009

Francis, C. (1992). *The Charlie Francis Training System*: TBLI Publications.

Froböse, I., Verdonck, A., Duesberg, F., & Mucha, C. (1993). Effects of various load intensities in the framework of postoperative stationary endurance training on performance deficit of the quadriceps muscle of the thigh. *Zeitschr Orthop, 131*, 164-167.

Fry, A. C. (1998). The role of training intensity in resistance exercise overtraining and overreaching. In R. B. Kreider, A. C. Fry & M. L. O'Toole (Eds.), *Overtraining in Sport* (pp. 107-130). Champaign, IL: Human Kinetics.

Fry, A. C., & Kraemer, W. J. (1991). Physical performance characteristics of american collegiate football players. *Journal of strength and conditioning research, 5*(3), 110-171.

Gabbett, T. J. (2009). Physiological and anthropometric characteristics of starters and non-starters in junior rugby league players, aged 13-17 years. *The Journal of sports medicine and physical fitness, 49*(3), 233-239.

Gabbett, T. J. (2010). GPS analysis of elite women's field hockey training and competition. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(5), 1321-1324. doi: 10.1519/JSC.0b013e3181ceebbb

Gabbett, T. J., Kelly, J. N., & Sheppard, J. M. (2008). Speed, change of direction speed, and reactive agility of rugby league players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 22*(1), 174-181. doi: 10.1519/JSC.0b013e31815ef700

Gabbett, T., Kelly, J., Ralph, S., & Driscoll, D. (2009). Physiological and anthropometric characteristics of junior elite and sub-elite rugby league players, with special reference to starters and non-starters. *Journal of science and medicine in sport, 12*, 215-222.

Gajer, B., Thepaut-Mathieu, C., & Lehenaff, D. (1999). Evoluation of stride and amplitude during course of the 100m event in athletics. *New studies in athletics, 14*(1), 43-50.

Gandevia, S. C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev, 81*(4), 1725-1789.

Gardiner, P. F. (1991). Effects of exercise training on components of the motor unit. *Canadian journal of sport sciences = Journal canadien des sciences du sport, 16*(4), 271-288.

Gardiner, P., Dai, Y., & Heckman, C. J. (2006). Effects of exercise training on alpha-motoneurons. *J Appl Physiol (1985), 101*(4), 1228-1236. doi: 10.1152/japplphysiol.00482.2006

Gissis, I., Papadopoulos, C., Kalapotharakos, V. I., Sotiropoulos, A., Komsis, G., & Manolopoulos, E. (2006). Strength and speed characteristics of elite, subelite, and recreational young soccer players. *Research in sports medicine, 14*(3), 205-214. doi: 10.1080/15438620600854769

Gittoes, M., Bezodis, I., & WIlson, C. (2011). *Intra-limb kinematic strategies of maximum velocity phase sprint running performances.* Paper presented at the International Society of Biomechanics in Sports, Porto, Portugal.

Goldspink, G. (1999). Changes in muscle mass and phenotype and the expression of autocrine and systemic growth factors by muscle in response to stretch and overload. *Journal of anatomy, 194 (Pt 3)*, 323-334.

Gottschall, J. S., & Kram, R. (2005). Ground reaction forces during downhill and uphill running. *Journal of biomechanics, 38*(3), 445-452. doi: 10.1016/j.jbiomech.2004.04.023

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Gregson, W., Drust, B., Atkinson, G., & Salvo, V. D. (2010). Match-to-match variability of high-speed activities in premier league soccer. *International journal of sports medicine, 31*(4), 237-242. doi: 10.1055/s-0030-1247546

Haff, G. G., Stone, M. H., O'Bryant, H. S., Harman, E. A., Dinan, C., Johnson, R., & Ki-Hoon, H. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of strength and conditioning research, 11*(4), 269-272.

Haff, G., & Nimphius, S. (2012). Training principles for power. *Strength & conditioning Journal, 34*(6), 2-12.

Haff, G., & Stone, M. H. (2015). Methods of developing power with special reference to football players. *Strength & conditioning Journal, 37*(6), 2-16.

Hakkinen, K. (1994). Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electromyogr Clin Neurophysiol, 34*(4), 205-214.

Hakkinen, K., Newton, R. U., Gordon, S. E., McCormick, M., Volek, J. S., Nindl, B. C., . . . Kraemer, W. J. (1998). Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and older men. *The journals of gerontology. Series A, Biological sciences and medical sciences, 53*(6), B415-423.

Harland, M. J., & Steele, J. R. (1997). Biomechanics of the sprint start. *Sports medicine, 23*(1), 11-20.

Harris, G. R., Stone, M. H., O'Bryant, H. S., Proulx, C. M., Johnson, R. L. (2000). Short-term performance effects of high power, high force, or combined weight training methods. *Journal of strength and conditioning research / National Strength & Conditioning Association, 14*(14-20).

Harrison, A. J., Keane, S. P., & Coglan, J. (2004). Force-velocity relationship and stretch-shortening cycle function in sprint and endurance athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 18*(3), 473-479. doi: 10.1519/13163.1

Haugen, T., Tonnessen, E., Hisdal, J., & Seiler, S. (2014). The role and development of sprinting speed in soccer. *International journal of sports physiology and performance, 9*(3), 432-441. doi: 10.1123/ijspp.2013-0121

Hawley, J. A., Williams, M. M., Vickovic, M. M., & Handcock, P. J. (1992). Muscle power predicts freestyle swimming performance. *British journal of sports medicine, 26*(3), 151-155.

Henneman, E., Somjen, G., & Carpenter, D. O. (1965). Excitability and inhibitility of motorneurons of different sizes. *Journal of neurophysiology, 28*(3), 599-620.

Hewit, J. K., Cronin, J. B., & Hume, P. A. (2013). Kinematic factors affecting fast and slow straight and change-of-direction acceleration times. *Journal of strength and conditioning research / National Strength & Conditioning Association, 27*(1), 69-75. doi: 10.1519/JSC.0b013e31824f202d

Hoare, D. G. (2000). Predicting success in junior elite basketball players--the contribution of anthropometic and physiological attributes. *Journal of science and medicine in sport / Sports Medicine Australia, 3*(4), 391-405.

Hoffman, J. H. (2014). *An investigation of the sled push exercise: Quantification of work, kinematics, and related physical characteristics.* (Doctor of Philosophy in Sport Physiology and Performance), East Tennessee State University, Johnson City, TN.

Hoffman, J. R., Tenenbaum, G., Maresh, C. M., & Kraemer, W. J. (1996). Relationship between athletic performance tests and playing time in elite college basketball players. *Journal of strength and conditioning research, 10*(2), 67-71.

Hoffman, J. R., Vazquez, J., Pichardo, N., & Tenenbaum, G. (2009). Anthropometric and performance comparisons in professional baseball players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 23*(8), 2173-2178. doi: 10.1519/JSC.0b013e3181bcd5fe

Hopkins, W. (2015). A scale of magnitude for effect statistics. Retrieved January, 2015, from http://sportsci.org/resource/stats/effectmag.html

Hornsby, W. G. (2013). *A systematic approach to the monitoring of competitive weightlifters.* (Doctorate of Philosophy in Sport Physiology and Performance), East Tennessee State University, Johnson City, TN.

Hrysomallis, C. (2012). The effectiveness of resisted movement training on sprinting and jumping performance. *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(1), 299-306. doi: 10.1519/JSC.0b013e3182185186

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Segment-interaction analysis of the stance limb in sprint running. *Journal of biomechanics, 37*(9), 1439-1446. doi: 10.1016/j.jbiomech.2003.12.018

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of applied biomechanics, 21*(1), 31-43.

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *The Journal of sports medicine and physical fitness, 48*(1), 65-75.

Issurin, V. B. (2010). New horizons for the methodology and physiology of training periodization. *Sports medicine, 40*(3), 189-206. doi: 10.2165/11319770-000000000-00000

Jacobs, R., & van Ingen Schenau, G. J. (1992). Intermuscular coordination in a sprint push-off. *Journal of biomechanics, 25*(9), 953-965.

Jahnke, M. T., Proske, U., & Struppler, A. (1989). Measurements of muscle stiffness, the electromyogram and activity in single muscle spindles of human flexor muscles following conditioning by passive stretch or contraction. *Brain Res, 493*(1), 103-112.

Jaric, S., Ristanovic, D., & Corcos, D. M. (1989). The relationship between muscle kinetic parameters and kinematic variables in a complex movement. *European journal of applied physiology and occupational physiology, 59*(5), 370-376.

Johnston, R. D., Gabbett, T. J., Jenkins, D. G., & Hulin, B. T. (2015). Influence of physical qualities on post-match fatigue in rugby league players. *Journal of science and medicine in sport / Sports Medicine Australia, 18*(2), 209-213. doi: 10.1016/j.jsams.2014.01.009

Jovanovic, M., Sporis, G., Omrcen, D., & Fiorentini, F. (2011). Effects of speed, agility, quickness training method on power performance in elite soccer players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 25*(5), 1285-1292. doi: 10.1519/JSC.0b013e3181d67c65

Kawakami, Y., Abe, T., & Fukunaga, T. (1993). Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *J Appl Physiol (1985), 74*(6), 2740-2744.

Kawakami, Y., Muraoka, Y., Kubo, K., Suzuki, Y., & Fukunaga, T. (2000). Changes in muscle size and architecture following 20 days of bed rest. *J Gravit Physiol, 7*(3), 53-59.

Kawamori, N., Newton, R. U., Hori, N., & Nosaka, K. (2014). Effects of weighted sled towing with heavy versus light load on sprint acceleration ability. *Journal of strength and conditioning research / National Strength & Conditioning Association, 28*(10), 2738-2745. doi: 10.1519/JSC.0b013e3182915ed4

Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 27*(3), 568-573. doi: 10.1519/JSC.0b013e318257805a

Kinser, A. M., Ramsey, M. W., O'Bryant, H. S., Ayres, C. A., Sands, W. A., & Stone, M. H. (2008). Vibration and stretching effects on flexibility and explosive strength in young gymnasts. *Medicine and science in sports and exercise, 40*(1), 133-140. doi: 10.1249/mss.0b013e3181586b13

Kivi, D., & Alexander, M. (1997). *A kinematic comparison of the running A and B drills with sprinting.* University of Manitoba, Manitoba, Canada.

Komi, P. V. (2008). Stretch-shortening cycle. In P. V. Komi (Ed.), *Strength and power in sport* (2nd ed., pp. 184-202). Oxford, UK: Blackwell Science Ltd.

Kraemer, W. J. (1992a). Endocrine responses and adaptations to strength training. In P. V. Komi (Ed.), *Strength and power in sport* (pp. 291-304). Oxford: Blackwell Scientific.

Kraemer, W. J., Marchitelli, L., Gordon, S. E., Harman, E., Dziados, J. E., Mello, R., . . . Fleck, S. J. (1990). Hormonal and growth factor responses to heavy resistance exercise protocols. *J Appl Physiol (1985), 69*(4), 1442-1450.

Kraska, J. M., Ramsey, M. W., Haff, G. G., Fethke, N., Sands, W. A., Stone, M. E., & Stone, M. H. (2009). Relationship between strength characteristics and unweighted and weighted vertical jump height. *International journal of sports physiology and performance, 4*(4), 461-473.

Krause, D. A., Smith, A. M., Holmes, L. C., Klebe, C. R., Lee, J. B., Lundquist, K. M., . . . Hollman, J. H. (2012). Relationship of off-ice and on-ice performance measures in high school male hockey players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(5), 1423-1430. doi: 10.1519/JSC.0b013e318251072d

Kugler, F., & Janshen, L. (2010). Body position determines propulsive forces in accelerated running. *Journal of biomechanics, 43*(2), 343-348. doi: 10.1016/j.jbiomech.2009.07.041

Kuipers, H. (1996). How much is too much? Performance aspects of overtraining. *Research quarterly for exercise and sport, 67*(3 Suppl), S65-69.

Kuitunen, S., Komi, P. V., & Kyrolainen, H. (2002). Knee and ankle joint stiffness in sprint running. *Medicine and science in sports and exercise, 34*(1), 166-173.

Lecker, S. H., Goldberg, A. L., & Mitch, W. E. (2006). Protein degradation by the ubiquitin-proteasome pathway in normal and disease states. *J Am Soc Nephrol, 17*(7), 1807-1819. doi: 10.1681/ASN.2006010083

Letzelter, M., Sauerwein, G., & Burger, R. (1995). Resistance runs in speed development. *Modern athlete and coach, 33*, 7-12.

Lloyd, R. S., Oliver, J. L., Hughes, M. G., & Williams, C. A. (2012). The effects of 4-weeks of plyometric training on reactive strength index and leg stiffness in male youths. *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(10), 2812-2819. doi: 10.1519/JSC.0b013e318242d2ec

Lockie, R. G., Murphy, A. J., & Spinks, C. D. (2003). Effects of resisted sled towing on sprint kinematics in field-sport athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 17*(4), 760-767.

Lockie, R. G., Murphy, A. J., Knight, T. J., & Janse de Jonge, X. A. (2011). Factors that differentiate acceleration ability in field sport athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 25*(10), 2704-2714. doi: 10.1519/JSC.0b013e31820d9f17

Lockie, R. G., Murphy, A. J., Schultz, A. B., Jeffriess, M. D., & Callaghan, S. J. (2013). Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 27*(9), 2494-2503. doi: 10.1519/JSC.0b013e31827f5103

Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J., & Janse de Jonge, X. A. (2012). The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 26*(6), 1539-1550. doi: 10.1519/JSC.0b013e318234e8a0

Lopez-Segovia, M., Marques, M. C., van den Tillaar, R., & Gonzalez-Badillo, J. J. (2011). Relationships between vertical jump and full squat power outputs with sprint times in u21 soccer players. *Journal of human kinetics, 30*, 135-144. doi: 10.2478/v10078-011-0081-2

Luebbers, P. E., Potteiger, J. A., Hulver, M. W., Thyfault, J. P., Carper, M. J., & Lockwood, R. H. (2003). Effects of plyometric training and recovery on vertical jump performance and anaerobic power. *Journal of strength and conditioning research / National Strength & Conditioning Association, 17*(4), 704-709.

Mackala, K. (2007). Optimisation of performance through kinematic analysis of the different phases of the 100 metres. *New studies in athletics, 22*(2), 7-16.

Mackala, K., Fostiak, M., & Kowalski, K. (2015). Selected determinants of acceleration in the 100m sprint. *Journal of human kinetics, 45*, 135-148. doi: 10.1515/hukin-2015-0014

Maganaris, C. N. (2001). Force-length characteristics of in vivo human skeletal muscle. *Acta physiologica Scandinavica, 172*(4), 279-285. doi: 10.1046/j.1365-201x.2001.00799.x

Mann, R. V. (2013). *The mechanics of sprinting and hurdling*. Charlestown, SC.

Markovic, G., & Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports medicine, 40*(10), 859-895. doi: 10.2165/11318370-000000000-00000

Marques, M. C., & Izquierdo, M. (2014). Kinetic and kinematic associations between vertical jump performance and 10-m sprint time. *Journal of strength and conditioning research / National Strength & Conditioning Association, 28*(8), 2366-2371. doi: 10.1519/JSC.0000000000000390

Marques, M. C., Gil, H., Ramos, R. J., Costa, A. M., & Marinho, D. A. (2011). Relationships between vertical jump strength metrics and 5 meters sprint time. *Journal of human kinetics, 29*, 115-122. doi: 10.2478/v10078-011-0045-6

Marshall, P. W., McEwen, M., & Robbins, D. W. (2011). Strength and neuromuscular adaptation following one, four, and eight sets of high intensity resistance exercise in trained males. *European journal of applied physiology, 111*(12), 3007-3016. doi: 10.1007/s00421-011-1944-x

Martinez-Valencia, M. A., Romero-Arenas, S., Elvira, J. L., Gonzalez-Rave, J. M., Navarro-Valdivielso, F., & Alcaraz, P. E. (2015). Effects of Sled Towing on Peak Force, the Rate

of Force Development and Sprint Performance During the Acceleration Phase. *Journal of human kinetics, 46*, 139-148. doi: 10.1515/hukin-2015-0042
Journal of human kinetics, 46, 139-148. doi: 10.1515/hukin-2015-0042

McBride, J. M., Blow, D., Kirby, T. J., Haines, T. L., Dayne, A. M., & Triplett, N. T. (2009). Relationship between maximal squat strength and five, ten, and forty yard sprint times. *Journal of strength and conditioning research / National Strength & Conditioning Association, 23*(6), 1633-1636. doi: 10.1519/JSC.0b013e3181b2b8aa

McFarlane, B. (1993). A basic and advanced techical model for speed. *National strength and conditioning association journal, 15*(5), 57-61.

Meijer, J. P., Jaspers, R. T., Rittweger, J., Seynnes, O. R., Kamandulis, S., Brazaitis, M., . . . Degens, H. (2015). Single muscle fibre contractile properties differ between body-builders, power athletes and control subjects. *Exp Physiol, 100*(11), 1331-1341. doi: 10.1113/EP085267

Meir, R., Colla, P., & Milligan, C. (2001). Impact of the 10-metre rule change on professional rugby league: Implications for training. *Strength & conditioning Journal, 23*(6), 42-46.

Mero, A. (1988). Force-time characteristics and running vleocity of male sprinters acceleration phase of sprinting. *Research quarterly for exercise and sport, 59*(2), 94-98.

Mero, A., Komi, P. V., & Gregor, R. J. (1992). Biomechanics of sprint running. A review. *Sports medicine, 13*(6), 376-392.

Minetti, A. E. (2002). On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. *European journal of applied physiology, 86*(4), 363-369.

Morin, J. B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J. R. (2012). Mechanical determinants of 100-m sprint running performance. *European journal of applied physiology, 112*(11), 3921-3930. doi: 10.1007/s00421-012-2379-8

Morin, J. B., Slawinski, J., Dorel, S., de Villareal, E. S., Couturier, A., Samozino, P., . . . Rabita, G. (2015). Acceleration capability in elite sprinters and ground impulse: Push more, brake less? *Journal of biomechanics, 48*(12), 3149-3154. doi: 10.1016/j.jbiomech.2015.07.009

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med, 58*(3), 115-130.

Murphy, A. J., Lockie, R. G., & Coutts, A. J. (2003). Kinematic determinants of early acceleration in field sport athletes. *Journal of sports science & medicine, 2*(4), 144-150.

Nader, G. A. (2006). Concurrent strength and endurance training: from molecules to man. *Medicine and science in sports and exercise, 38*(11), 1965-1970. doi: 10.1249/01.mss.0000233795.39282.33

Nagahara, R., Matsubayashi, T., Matsuo, A., & Zushi, K. (2014). Kinematics of transition during human accelerated sprinting. *Biology open, 3*(8), 689-699. doi: 10.1242/bio.20148284

Nagahara, R., Naito, H., Morin, J. B., & Zushi, K. (2014). Association of acceleration with spatiotemporal variables in maximal sprinting. *International journal of sports medicine, 35*(9), 755-761. doi: 10.1055/s-0033-1363252

Newton, R. U., & Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength & conditioning Journal, 16*, 20-31.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2012). Changes in muscle architecture and performance during a competitive season in female softball players. *Journal of strength*

and conditioning research / National Strength & Conditioning Association, 26(10), 2655-2666. doi: 10.1519/JSC.0b013e318269f81e

Painter, K. B., Haff, G. G., Ramsey, M. W., McBride, J., Triplett, T., Sands, W. A., . . . Stone, M. H. (2012). Strength gains: block versus daily undulating periodization weight training among track and field athletes. *International journal of sports physiology and performance, 7*(2), 161-169.

Perez-Gomez, J., Olmedillas, H., Delgado-Guerra, S., Ara, I., Vicente-Rodriguez, G., Ortiz, R. A., . . . Calbet, J. A. (2008). Effects of weight lifting training combined with plyometric exercises on physical fitness, body composition, and knee extension velocity during kicking in football. *Applied physiology, nutrition, and metabolism = Physiologie appliquee, nutrition et metabolisme, 33*(3), 501-510. doi: 10.1139/H08-026

Peterson, M. D., Alvar, B. A., & Rhea, M. R. (2006). The contribution of maximal force production to explosive movement among young collegiate athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association, 20*(4), 867-873. doi: 10.1519/R-18695.1

Peyer, K. L., Pivarnik, J. M., Eisenmann, J. C., & Vorkapich, M. (2011). Physiological characteristics of National Collegiate Athletic Association Division I ice hockey players and their relation to game performance. *Journal of strength and conditioning research / National Strength & Conditioning Association, 25*(5), 1183-1192. doi: 10.1519/JSC.0b013e318217650a

Rabita, G., Dorel, S., Slawinski, J., Saez-de-Villarreal, E., Couturier, A., Samozino, P., & Morin, J. B. (2015). Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. *Scand J Med Sci Sports, 25*(5), 583-594. doi: 10.1111/sms.12389

Rahmani, A., Locatelli, E., & Lacour, J. R. (2004). Differences in morphology and force/velocity relationship between Senegalese and Italian sprinters. *European journal of applied physiology, 91*(4), 399-405. doi: 10.1007/s00421-003-0989-x

Reilly, T., Williams, A. M., Nevill, A., & Franks, A. (2000). A multidisciplinary approach to talent identification in soccer. *Journal of sports sciences, 18*(9), 695-702. doi: 10.1080/02640410050120078

Rienzi, E., Drust, B., Reilly, T., Carter, J. E., & Martin, A. (2000). Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *The Journal of sports medicine and physical fitness, 40*(2), 162-169.

Rimmer, E., & Sleivert, G. (2000). Effects of a plyometrics intervention program on sprint performance. *Journal of strength and conditioning research, 14*(3), 295-301.

Ronnestad, B. R., Kvamme, N. H., Sunde, A., & Raastad, T. (2008). Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 22*(3), 773-780. doi: 10.1519/JSC.0b013e31816a5e86

Ross, A., & Leveritt, M. (2001). Long-term metabolic and skeletal muscle adaptations to short-sprint training: implications for sprint training and tapering. *Sports medicine, 31*(15), 1063-1082.

Ross, A., Leveritt, M., & Riek, S. (2001). Neural influences on sprint running: training adaptations and acute responses. *Sports medicine, 31*(6), 409-425.

Rumpf, M. C., Lockie, R. G., Cronin, J. B., & Jalilvand, F. (2015). The effect of different sprint training methods on sprint performance over various distances: a brief review. *Journal of*

strength and conditioning research / National Strength & Conditioning Association. doi: 10.1519/JSC.0000000000001245

Salmons, S., & Vrbova, G. (1969). The influence of activity on some contractile characteristics of mammalian fast and slow muscles. *The Journal of physiology, 201*(3), 535-549.

Sams, M. L. (2014). *Comparison of static and countermovement jump variables in relation to estimated training load and subjective measures of fatigue.* (Master of Arts in Kinesiology and Sport Studies), East Tennessee State University.

Schoenfeld, B. J., Aragon, A. A., & Krieger, J. W. (2013). The effect of protein timing on muscle strength and hypertrophy: a meta-analysis. *Journal of the International Society of Sports Nutrition, 10*(1), 53. doi: 10.1186/1550-2783-10-53

Seitz, L. B., Barr, M., & Haff, G. G. (2014). Effects of Sprint Training With or Without Ball Carry in Elite Rugby Players. *International journal of sports physiology and performance*. doi: 10.1123/ijspp.2014-0193

Seitz, L. B., Reyes, A., Tran, T. T., Saez de Villarreal, E., & Haff, G. G. (2014). Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. *Sports medicine, 44*(12), 1693-1702. doi: 10.1007/s40279-014-0227-1

Seynnes, O. R., de Boer, M., & Narici, M. V. (2007). Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol (1985), 102*(1), 368-373. doi: 10.1152/japplphysiol.00789.2006

Sha, Z. (2014). *Kinetic and kinematic properties of D-I male sprinters.* (Doctorate of Philosophy in Sport Physiology and Performance), East Tennessee State University, Johnson City, TN.

Shalfawi, S. A., Sabbah, A., Kailani, G., Tonnessen, E., & Enoksen, E. (2011). The relationship between running speed and measures of vertical jump in professional basketball players: A field-test approach. *Journal of strength and conditioning research, 25*(11), 3088-3092.

Siff, M. C. (2009). *Supertraining* (6th ed.). Rome: Ultimate Athlete Concepts.

Slawinski, J., Bonnefoy, A., Leveque, J. M., Ontanon, G., Riquet, A., Dumas, R., & Cheze, L. (2010). Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *Journal of strength and conditioning research / National Strength & Conditioning Association, 24*(4), 896-905. doi: 10.1519/JSC.0b013e3181ad3448

Sleivert, G., & Taingahue, M. (2004). The relationship between maximal jump-squat power and sprint acceleration in athletes. *European journal of applied physiology, 91*(1), 46-52. doi: 10.1007/s00421-003-0941-0

Smiles, W. J., Hawley, J. A., & Camera, D. M. (2016). Effects of skeletal muscle energy availability on protein turnover responses to exercise. *J Exp Biol, 219*(Pt 2), 214-225. doi: 10.1242/jeb.125104

Smirniotou, A., Katsikas, C., Paradisis, G., Argeitaki, P., Zacharogiannis, E., & Tziortzis, S. (2008). Strength-power parameters as predictors of sprinting performance. *The Journal of sports medicine and physical fitness, 48*(4), 447-454.

Smith, L. L. (2000). Cytokine hypothesis of overtraining: a physiological adaptation to excessive stress? *Medicine and science in sports and exercise, 32*(2), 317-331.

Sole, C. J. (2015). *Analysis of countermovement jump force-time curve phase characteristics in athletes.* (Doctorate of Philosophy in Sport Physiology and Performance), East Tennessee State University, Johnson City, TN.

Spinks, C. D., Murphy, A. J., Spinks, W. L., & Lockie, R. G. (2007). The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and

Australian football players. *Journal of strength and conditioning research / National Strength & Conditioning Association, 21*(1), 77-85. doi: 10.1519/R-18145.1

Stone, M. H., Keith, R., Kearnery, J. T., Fleck, S. J., Wilson, G. D., & Triplett, N. T. (1991b). Overtraining: A review of the signs and symptoms and possible causes of overtraining. *Journal of applied sport science research, 5*, 35-50.

Stone, M. H., Moir, G., Glaister, M., Sanders, R. (2002). How much strength is necessary? *Phys Ther Sport, 3*, 88-96.

Stone, M. H., O'Bryant, H. S., McCoy, L., Coglianese, R., Lehmkuhl, M., & Schilling, B. (2003). Power and maximum strength relationships during performance of dynamic and static weighted jumps. *Journal of strength and conditioning research / National Strength & Conditioning Association, 17*(1), 140-147.

Stone, M. H., O'Bryant, H. S., Schilling, B. K., & Johnson, R. L. (1999). Periodization: Effects of manipulating volume and intensity. Part 2. *Strength & conditioning Journal, 21*(3), 54-60.

Stone, M. H., Plisk, S. S., Stone, M. E., Schilling, B. K., O'Bryant, H. S., & Pierce, K. C. (1998). Athletic performance development: volume load - 1 set versus multiple sets, training velocity and training variation. *Strength & conditioning Journal, 20*, 22-31.

Stone, M. H., Sanborn, K., O'Bryant, H. S., Hartman, M., Stone, M. E., Proulx, C., . . . Hruby, J. (2003). Maximum strength-power-performance relationships in collegiate throwers. *Journal of strength and conditioning research / National Strength & Conditioning Association, 17*(4), 739-745.

Stone, M. H., Sands, W. A., Pierce, K. C., Carlock, J., Cardinale, M., & Newton, R. U. (2005). Relationship of maximum strength to weightlifting performance. *Medicine and science in sports and exercise, 37*(6), 1037-1043.

Stone, M. H., Stone, M., Sands, W. A. (2007). *Principles and Practice of Strength Training*. Champaign, IL: Human Kinetics.

Taber, C., Bellon, C. R., Abbott, H., & Bingham, G. E. (2016). Roles of maximal strength and rate of force development in maximizing muscular power. *Strength & conditioning Journal, 38*(1), 71-78.

Thomas, C., Comfort, P., Chiang, C.-Y., & Jones, P. A. (2015). Relationship between isometric mid-thigh pull variables and sprint change of direction in collegiate athletes. *Journal of trainology, 4*(1), 6-10.

Tillin, N. A., & Bishop, D. (2009). Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports medicine, 39*(2), 147-166. doi: 10.2165/00007256-200939020-00004

Trappe, S., Luden, N., Minchev, K., Raue, U., Jemiolo, B., & Trappe, T. A. (2015). Skeletal muscle signature of a champion sprint runner. *J Appl Physiol (1985), 118*(12), 1460-1466. doi: 10.1152/japplphysiol.00037.2015

Verkhoshansky, Y. V. (1985). *Programming and organization of training*. Livonia, MI: Sportivny Press.

Vigne, G., Gaudino, C., Rogowski, I., Alloatti, G., & Hautier, C. (2010). Activity profile in elite Italian soccer team. *International journal of sports medicine, 31*(5), 304-310. doi: 10.1055/s-0030-1248320

Wakahara, T., Fukutani, A., Kawakami, Y., & Yanai, T. (2013). Nonuniform muscle hypertrophy: its relation to muscle activation in training session. *Medicine and science in sports and exercise, 45*(11), 2158-2165. doi: 10.1249/MSS.0b013e3182995349

Walsh, M., Arampatzis, A., Schade, F., & Bruggemann, G. P. (2004). The effect of drop jump starting height and contact time on power, work performed, and moment of force. *Journal of strength and conditioning research / National Strength & Conditioning Association, 18*(3), 561-566. doi: 10.1519/1533-4287(2004)18<561:TEODJS>2.0.CO;2

Wang, R., Hoffman, J. R., Tanigawa, S., Miramonti, A. A., La Monica, M. B., Beyer, K. S., . . . Jeffrey, S. R. (2016). Isometric Mid-Thigh Pull Correlates with Strength, Sprint and Agility Performance in Collegiate Rugby Union Players. *Journal of strength and conditioning research / National Strength & Conditioning Association*. doi: 10.1519/JSC.0000000000001416

West, D. W., Burd, N. A., Staples, A. W., & Phillips, S. M. (2010). Human exercise-mediated skeletal muscle hypertrophy is an intrinsic process. *Int J Biochem Cell Biol, 42*(9), 1371-1375. doi: 10.1016/j.biocel.2010.05.012

Weyand, P. G., Sandell, R. F., Prime, D. N., & Bundle, M. W. (2010). The biological limits to running speed are imposed from the ground up. *Journal of applied physiology, 108*(4), 950-961. doi: 10.1152/japplphysiol.00947.2009

Weyand, P. G., Sternlight, D. B., Bellizzi, M. J., & Wright, S. (2000). Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *Journal of applied physiology, 89*(5), 1991-1999.

Winwood, P. W., Posthumus, L. R., Cronin, J. B., & Keogh, J. W. L. (2015). The acute potentiating effects of heavy sled pulls on sprint performance. *Journal of strength and conditioning research*. doi: 10.1519/JSC.0000000000001227

Young, W. (1992). Plyometrics: Sprint bounding and the sprint bound index. *Strength & conditioning Journal, 14*(4), 18-21.

Young, W. B. (2006). Transfer of strength and power training to sports performance. *International journal of sports physiology and performance, 1*(2), 74-83.

Young, W., McLean, B., & Ardagna, J. (1995). Relationship between strength qualities and sprinting performance. *The Journal of sports medicine and physical fitness, 35*(1), 13-19.

Zafeiridis, A., Saraslanidis, P., Manou, V., Ioakimidis, P., Dipla, K., & Kellis, S. (2005). The effects of resisted sled-pulling sprint training on acceleration and maximum speed performance. *The Journal of sports medicine and physical fitness, 45*(3), 284-290.

Zamparo, P., Minetti, A. E., & di Prampero, P. E. (2002). Interplay among the changes of muscle strength, cross-sectional area and maximal explosive power: theory and facts. *European journal of applied physiology, 88*(3), 193-202. doi: 10.1007/s00421-002-0691-4

Zanchi, N. E., & Lancha, A. H., Jr. (2008). Mechanical stimuli of skeletal muscle: implications on mTOR/p70s6k and protein synthesis. *European journal of applied physiology, 102*(3), 253-263. doi: 10.1007/s00421-007-0588-3

Zatsiorsky, V. M., & Kraemer, W. J. (2006). *Science and practice of strength training* (2nd ed.). Champaign, IL: Human Kinetics.

Zehr, E. P., & Sale, D. G. (1994). Ballistic movement: muscle activation and neuromuscular adaptation. *Can J Appl Physiol, 19*(4), 363-378.

APPENDICES

APPENDIX A: ETSU Institutional Review Board Approval

EAST TENNESSEE STATE
U N I V E R S I T Y

Office for the Protection of Human Research Subjects • Box 70565 • Johnson City, Tennessee 37614-1707
Phone: (423) 439-6053 Fax: (423) 439-6060

IRB APPROVAL – Initial Expedited Review

October 8, 2015

Christopher Bellon

Re: The Relationship between Strength, Power, and Sprint Acceleration in Team Sport Athletes
IRB#: c0915.18s
ORSPA #:

The following items were reviewed and approved by an expedited process:
- 107 xForm, PI CV, References, ICD, inclusion/exclusion survey

The following revisions were received and approved as part of the requested changes:
- Requested changes xForm, Revisions to protocol, Revised ICD

On **October 8, 2015**, a final approval was granted for a period not to exceed 12 months and will expire on **October 7, 2016**. The expedited approval of the study *and* requested changes will be reported to the convened board on the next agenda.

The following **enclosed stamped, approved Informed Consent Documents** have been stamped with the approval and expiration date and these documents must be copied and provided to each participant prior to participant enrollment:
- Informed Consent Document (ICD (ver 8-18-15 SA 10-8-15))

Federal regulations require that the original copy of the participant's consent be maintained in the principal investigator's files and that a copy is given to the subject at the time of consent.

Projects involving Mountain States Health Alliance must also be approved by MSHA following IRB approval prior to initiating the study.

Unanticipated Problems Involving Risks to Subjects or Others must be reported to the IRB (and VA R&D if applicable) within 10 working days.

Proposed changes in approved research cannot be initiated without IRB review and approval. The only exception to this rule is that a change can be made prior to IRB approval when necessary to

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eliminate apparent immediate hazards to the research subjects [21 CFR 56.108 (a)(4)]. In such a case, the IRB must be promptly informed of the change following its implementation (within 10 working days) on Form 109 (www.etsu.edu/irb). The IRB will review the change to determine that it is consistent with ensuring the subject's continued welfare.

Sincerely,
Stacey Williams, Chair
ETSU Campus IRB

APPENDIX B: ETSU Informed Consent Document

PRINCIPAL INVESTIGATOR: _____ Christopher Bellon _____

TITLE OF Study: The relationship between strength, power, and sprint acceleration in team sport athletes

Informed Consent Form

Introduction:

This Informed Consent will explain about being a participant in a research study. It is important that you read this material carefully and then decide if you wish to be a volunteer.

Purpose:

The purposes of the study are the following:
1. To identify which strength and power variables are most related to sprint acceleration performance in team sport athletes.
2. To determine the differences in sprint acceleration characteristics (e.g. stride length and stride frequency) in "strong" versus "weak" and "fast" versus "slow" team sport athletes.

DURATION:

All data will be collected during a single testing session that will take each participant approximately 75-minutes to complete.

PROCEDURES:

1. Hydration and anthropometrics (e.g. height and weight)
2. Standardized warm-up
3. Static jumps on force platforms
4. Countermovement jumps on force platforms
5. Isometric mid-thigh pulls
6. 20-meter sprint trials

ALTERNATIVE PROCEDURES/TREATMENTS:

There are no alternative procedures except not to participate.

POSSIBLE RISKS/DISCOMFORTS:

Any potential risk in this study design is minimal, as the participants will not be exposed to any stresses greater than what they are accustomed to in their training. As with any training experience, however, the participants may experience residual soreness in the musculature of the legs in the days following the testing session.

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PRINCIPAL INVESTIGATOR: _____ Christopher Bellon_____

TITLE OF Study: The relationship between strength, power, and sprint acceleration in team sport athletes

POSSIBLE BENEFITS:

Participants will undergo a battery of strength and power tests designed to assess their athletic ability with cutting edge technology. Each participant's results will be compared to normative data from previous testing sessions with other collegiate athletes to identify their individual strengths and weaknesses. This information will be sent via email upon the request of the participant at the conclusion of data collection.

FINANCIAL COSTS:

There are no financial costs to you.

COMPENSATION IN THE FORM OF PAYMENTS TO RESEARCH PARTICIPANTS:

There is no compensation for your participation in this research.

VOLUNTARY PARTICIPATION:

Participation in this research experiment is voluntary. You may refuse to participate. You can withdraw at any time. If you quit or refuse to participate, the benefits or treatment to which you are otherwise entitled will not be affected. Refusing to participate in this study will not impact your grades if you are enrolled in a class taught by a Sports Science staff member. You may withdraw by contacting Chris Bellon at (423) 439-4757 or email at bellon@goldmail.etsu.edu.

CONTACT FOR QUESTIONS:

If you have any questions, problems or research-related medical problems at any time, you may contact Chris Bellon at (423) 439-4757 or email at bellon@goldmail.etsu.edu. You may call the Chairman of the Institutional Review Board at 423-439-6054 for any questions you may have about your rights as a research subject. If you have any questions or concerns about the research and want to talk to someone independent of the research team or you can't reach the study staff, you may call an IRB Coordinator at 423-439-6055 or 423-439-6002.

CONFIDENTIALITY:

Every attempt will be made to see that your study results are kept confidential. A copy of the records from this study will be stored in a locked drawer in E113 for at least 5 years after the end of this research. The results of this study may be published and/or presented at meetings without naming you as a subject. Although your rights and privacy will be maintained, the Secretary of the Department of Health and Human Services, the

Ver. 06/18/15   Page 2 of 3   Subject Initials _____

PRINCIPAL INVESTIGATOR: _____Christopher Bellon_____

TITLE OF Study: The relationship between strength, power, and sprint acceleration in team sport athletes

ETSU IRB, and the Exercise and Sport Science department will have access to the study records. Your records will be kept completely confidential according to current legal requirements. They will not be revealed unless required by law, or as noted above.

By signing below, you confirm that you have read or had this document read to you. You will be given a signed copy of this informed consent document. You have been given the chance to ask questions and to discuss your participation with the investigator. You freely and voluntarily choose to be in this research project. By signing this form, you are confirming that you are at least 18 years of age.

_____   _____
SIGNATURE OF PARTICIPANT   DATE

_____   _____
PRINTED NAME OF PARTICIPANT   DATE

_____   _____
SIGNATURE OF INVESTIGATOR   DATE

_____   _____
SIGNATURE OF WITNESS (if applicable)   DATE

APPENDIX C: Additional Data from Chapter 5

Table 5.12 Differences in sprint velocity between acceleration zones

Acceleration Zone Comparison	*p*-value	95% CI for difference (m/s)
Zone 3 versus Zone 2	0.000	0.82 –1.21
Zone 3 versus Zone 1	0.000	2.30 – 2.65
Zone 2 versus Zone 1	0.000	1.29 – 1.63

Table 5.13 Differences in step length between acceleration zones

Acceleration Zone Comparison	*p*-value	95% CI for difference (cm)
Zone 3 versus Zone 2	0.000	16.72 – 21.93
Zone 3 versus Zone 1	0.000	45.76 – 50.95
Zone 2 versus Zone 1	0.000	25.54 – 32.52

Table 5.14 Differences in step frequency between acceleration zones

Acceleration Zone Comparison	*p*-value	95% CI for difference (steps/sec)
Zone 3 versus Zone 2	0.000	0.03 – 0.20
Zone 3 versus Zone 1	0.000	0.08 – 0.35
Zone 2 versus Zone 1	0.000	0.00 – 0.259

Table 5.15 Differences in ground contact time between acceleration zones

Acceleration Zone Comparison	*p*-value	95% CI for difference (ms)
Zone 3 versus Zone 2	0.000	5.79 – 13.78
Zone 3 versus Zone 1	0.000	20.14 – 30.11
Zone 2 versus Zone 1	0.000	10.31 – 20.37

VITA

CHRISTOPHER R. BELLON

Education: Ph.D. Sport Physiology and Performance, East Tennessee State University, Johnson City, TN, 2016

M.A. Exercise Science, Montclair State University, Montclair, NJ, 2013

B.S. Physical Education & Health (*Suma Cum Laude*), Montclair State University, Montclair, NJ, 2011

North Rockland High School, Thiells, NY, 2006

Professional Experience: Strength and Conditioning Coach/Sport Scientist, East Tennessee State University Women's Basketball, 2013-2015

Strength and Conditioning Coach/Sport Scientist, East Tennessee State University Track & Field, 2014-2015

Strength and Conditioning Coach/Sport Scientist, East Tennessee State University Women's Volleyball, 2016

Publications: Taber, C., Bellon, C. R., Abbott, H., & Bingham, G. E. (2016). Roles of maximal strength and rate of force development in maximizing muscular power. *Strength & conditioning Journal, 38*(1), 71-78.

Bazyler, C. D., Abbott, H. A., Bellon, C. R., Taber, C. B., and Stone, M. H. (2015). Strength training for endurance athletes: theory to practice. *Strength and conditioning journal, 37(2), 1-12.*