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Return-To-The-Platform: The Case of a Collegiate Level Weightlifter Recovering from a Meniscus Injury

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by

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ABSTRACT

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The purpose of this study was to observe physiological metrics relative to training-induced adaptations in conjunction with laboratory- and competition-based performances in a super-heavyweight weightlifter recovering from a meniscus injury. A retrospective analysis was conducted on a collegiate level male weightlifter (23.2 yrs; 131.9 kg; 187.3 cm) over the course of 21-weeks post-meniscus surgery. Body mass, body fat percentage, hydration status, vastus lateralis muscle cross-sectional area, jump performance, and isometric midthigh pull were regularly assessed as part of an ongoing athlete monitoring program. Pre-injury baseline (T0) measurements were collected relative to a major national competition (COMP1). Post-injury measurements took place at the end of sequential training blocks: strength-endurance training block 1 (T1), basic strength block 2 (T2), and transmutation block 3 (T3). The final measurement session (T4) was conducted three-days post-local competition (COMP2). Only statistically significant increases were observed from T0-T4 for muscle CSA (p=0.0367), isometric peak force (p<0.05), isometric peak force allometrically scaled to body mass (p=0.0367), and rate of force development at 250ms (p=.0367). While non-significant changes were observed for jumping performance, jump height and net impulse did, however, return to baseline. Competition based performances also showed marked improvements from pre-to-post injury via an increase in weightlifting total (3.2%Δ, +9kg) and Sinclair score (1.8%Δ, +5.3au). Thus, based on these findings, implementing an evidence-based training program along with a sound athlete

monitoring protocol can aid with reducing an athlete's return-to-train timeline while improving physiological, laboratory- and competition-based performance outcomes.

DEDICATION

Many deserve this dedication but none more than Jesus Christ. Let everything that has breath praise the LORD (Psalm 150:6).

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Chapter 1. Introduction

To be competitive in the sport of weightlifting, athletes must excel in both kinetic and kinematic abilities. However, weightlifting technique tends to stabilize within a few months (Ajan & Baroga, 1988; Kauhanen et al., 1984), while kinetic variables continue to improve (Garhammer, 1993; Cunanan et al., 2020). Additionally, evidence suggests that the magnitude of force and rate of force development (RFD), and impulse generated by the lifter is paramount to weightlifting success (Stone et al., 1998; Garhammer, 1980; Garhammer, 1985). Consequently, the performance of more advanced weightlifters is likely driven by the capacity to generate high forces, RFD, and peak power outputs (Stone et al., 2005) during the competition lifts of the snatch and clean and jerk. These characteristics are often developed through unique training periods designed to elicit specific adaptations to the neuromuscular system. Therefore, assessing both the magnitudes and timelines in which these adaptations occur can be useful for designing a training regime for strength and power athletes.

The isometric mid-thigh pull (IMTP) is a typically used method to assess both the kinetic ability of an athlete as well as monitor changes in their performance potential throughout a period of training (Hornsby et al., 2017). The IMTP is useful for monitoring of weightlifters because it provides the ability to safely measure critical performance variables such as peak force (PF), and rate of force development (RFD) in a sport-specific position, with strong correlations ($r \geq 0.70$) having been found between these variables and weightlifting performance (Beckham et al., 2013; Hornsby et al., 2017). However, RFD has been found to be more closely related to most athletic tasks (Maffiuletti et al., 2016) and is more sensitive to fatigue (Hornsby et al., 2017; Norris et al., 2018). Moreover, quantifying RFD in time bands appears to be more effective than only peak RFD (Haff et al., 2015), as RFD may be governed by different physiological mechanisms, such that earlier RFD time bands (<100 ms from onset) may be more influenced by neural factors and intrinsic muscle properties (Gruber & Gollhofer, 2004; Van Cutsem et al., 2004), while later time bands (≥150ms) are closely related to maximum muscle strength and size (Folland et al., 2014). Due to the size, architecture, and composition of muscle fibers influence on peak force and RFD (Aagaard & Thorstensson, 2008), muscle qualities such as muscle cross-sectional area are often assessed and monitored through ultrasonography (Hides et al., 1955).

Performance tests such as the squat jump (SJ) and countermovement jump (CMJ) are often used to detect fluctuations in power output, jump height, and dynamic RFD capabilities throughout the training cycles leading up to competition. In fact, they are a preferred monitoring tool when assessing weightlifting competition preparedness due to their limited interference with training, as well as biomechanical similarity to weightlifting activities (J. Garhammer, 1980; John Garhammer & Gregor, 1992). Indeed, peak power and jump height are purportedly significantly higher in weightlifters when compared to other athletes (Funato et al., 2000; Garhammer, 1980). In comparison to CMJ, static jumps have been shown to have somewhat superior associations with absolute and scaled weightlifting performance in male and female weightlifters (Carlock et al., 2004; Travis, Goodin, Suarez et al., 2017). Consequently, monitoring jump performance is a useful secondary measure to track weightlifting performance.

Injuries often occur in sport, with sports such as American football, basketball, and soccer experiencing 4.31-9.6 injuries per 1000 hours of training and play (Aasa et al., 2017; Prieto-Gonzalez et al., 2021). However, despite the explosive nature of strength sports such as weightlifting, powerlifting, strongman, and throwing events, injuries occur less frequently, with as few as 2.3-3.3 injuries per 1000 hours of training and play (Aasa et al., 2017; Keogh &

Winwood, 2017). Of these injuries, knee injuries tend to occur more frequently in sports such as weightlifting (Aasa et al., 2017). Unfortunately, the current literature regarding return-to-play, rehabilitation, and re-injury is lacking in relation to strength sports, focusing more on traditional sport (Bizzini, 2022; D'Lauro et al., 2018) or providing recommendations too broad for practicality (Ardern et al., 2016). To address rehabilitation of athletes, case studies are often used to track progress back to competition; however, they generally fail to provide detailed information about the specific training protocols used prior to, during, and after injury, sport specific monitoring tools, and changes in performance before and after injury to assess the efficacy of the intervention. Taken together, research is needed to provide practitioners with a rubric to guide rehabilitation of strength-power athletes such as weightlifters.

Block periodization is a framework used to sequentially produce specific adaptations across training phases, culminating in a peak in performance where the athlete has the highest likely performance on competition day (DeWeese et al. 2015; Stone et al. 2021). This form of periodization includes phases known as accumulation (general preparation), transmutation (special preparation), and realization (competition and taper) phases (Issurin, 2008; DeWeese et al., 2015b; Stone et al., 2021). This order of training phases is intended to develop work capacity and force generating potential early in the training cycle to potentiate the more specific training phases that follow in a logical and sequential way. However, using it as a means to rehabilitate athletes has not been produced in the current literature. It is possible that block periodization, combined with athlete monitoring tools such as the IMTP, jump performance, and ultrasonography, could serve as an effective means to prevent injuries and rehabilitate athletes interested in returning to the platform. Thus, the purpose of this observation is to retrospectively investigate 1) the efficacy using a block periodization-style rehabilitation training protocol, 2) the effectiveness of sport specific athlete monitoring to observe physiological adaptations, and 3) assess laboratory- and competition-based performance changes in a collegiate male weightlifter following a right knee meniscal injury.

Operational Definitions

1. Block: 3–5-week period of training that emphasizes specific qualities.
2. Countermovement jump: A type of vertical jump that begins with a countermovement.
3. Countermovement: A downward movement that precedes an upward movement.
4. Isometric Mid-Thigh Pull: A test of muscular strength conducted on fixed bar set inside of an adjustable rack. Subjects are placed in a position that mimics the second pull of a clean before performing an isometric pull as fast and hard as possible while standing on dual force plates.
5. Net-Impulse: The difference between the area under the force-time curve above and below system mass.
6. Peak Force: Highest force value found in a force-time curve.
7. Power: Product of force and velocity or rate of performing work.
8. Rate of Force Development: Change in force divided by change in time.
9. Sinclair: Calculation used to scale WL performance to body mass so that weightlifters can be compared across weight classes.
10. Strength: Ability of a muscle or group of muscles to produce force.

Chapter 2. Comprehensive Review of the Literature

Developing a training plan designed to maximize the physical development of an athlete is an important process, as the ability to lift heavy, run fast, or throw far has always been a simple but critical ability for most athletes. Indeed, these qualities are still desired and contested at the highest levels of sport in modern times. Achieving success in strength-power sports depends largely on the physical abilities of the athlete, making the evolution of qualities such as task specific hypertrophy, strength, and speed crucial when comparison to other sports. Due to this, it is crucial to create a sound, driven, and effective training process to develop serious strength-power athletes, which should be assessed through sport specific athlete monitoring tools.

Training and Periodization

The primary goal of training is to increase an athlete's potential of winning, which requires the athlete or group of athletes to perform better at their task than their competitor (Suarez et al., 2019). Although the primary determinant of winning in strength-power sports is strongly related to the genetics of the athletes (Bouchard et al., 1992; Huygens et al., 2004; Stone et al., 2007), it is mostly considered an uncontrollable aspect of the training process and therefore the physical, tactical, technical, and psychological preparation of the athlete becomes the only controllable aspect of winning or losing (Stone et al., 2007). This requires a long-term training plan based on the logical and evidence-based principles to guide the training process to most effectively prepare an athlete for success on the day of competition, including the use of block periodization, followed by implementation of sound training principles such as specificity, variation, and overload.

Planning the training process cannot be random, but instead requires the exploitation of training methods that serve a particular purpose (Suarez et al., 2019). Consequently, the most evident principle of training is the concept of specificity, which deals with the degree of mechanical or metabolic similarity between a training exercise or method and the actual competitive movement (DeWeese et al. 2015: Stone et al. 2007). However, one must also consider dynamic correspondence, a detailed strategy for comparing the specificity of movements (Verkoshansky & Siff, 2009; Suarez et al., 2019). Dynamic correspondence is a set of criteria that can be used to determine the level of specificity of movement by comparing the range of motion and directions of movements, the magnitudes and velocities of force application, the regions of force production, the type of muscular actions (e.g., concentric or eccentric), and the rate and time of force production (Goodwin & Cleather, 2016; Suarez et al., 2019). Although specificity is important, initial adaptations to any training strategy come with diminishing returns and require an eventual shift in stimulus to prevent stagnation. Consequently, variation, another important training principle, involves adjusting the training type, volume, intensity, and frequency to prolong athlete development and prevent boredom and injury from overuse (Kassiano et al., 2022; Bompa & Haff, 2009; Stone et al., 1991; Stone et al., 2021). The third training principle, overload, is the primary stimulus for eliciting desired adaptations (Stone et al., 2000) by disrupting the athlete's current levels of homeostasis, forcing the body to achieve levels of performance it has not previously (Suarez et al., 2019). This is achieved through the cyclical increase in volume, intensity, or frequency of training, causing a stress response (disrupting homeostasis). Indeed, this response can be partially explained by the General Adaptation Syndrome (GAS) originally developed by Hans Selye (1956), which has been related to the training process in athletes and used as part of the rationale for modern periodization (Cunanan et al., 2018; Haff, 2004a, 2004b; Zatsiorsky & Kraemer, 2006).

Periodization is built on four basic goals: (1) to elevate an athlete's performance at predetermined timepoints; (2) maximize specific physiological and performance adaptations at the appropriate time; (3) reduce the risk of non-functional overreaching and overtraining; and (4) provide for long-term athlete development (Bompa & Haff, 2009; Stone et al., 2021). Practically, periodization is a conceptual blueprint dealing with fitness phases and timelines that allow the coach to project an approximate timeline for when various types of fitness phases will be emphasized, as well as the order and duration of each phase (DeWeese et al., 2015; Stone et al., 2021). Although two types of periodization exist (traditional and block), block periodization is generally considered more effective for most sports compared relative to traditional periodization, as traditional periodization comes with limiting factors, including the inability to provide multi peak performances in close time proximity, simultaneous attempts to increase multi-factors can result in incompatibility of different training stimuli, and insufficient training stimulus (Issurin, 2008; Issurin, 2010). Conversely, block periodization, which can be broken down into single factor or multi factor, uses concentrated loading (blocks) which emphasizes one or a few characteristics of physiological development (i.e., endurance, strength, power, speed), while de-emphasizing other aspects of training through implementation of retaining loads (minimal doses to maintain specific fitness characteristics; DeWeese et al., 2015; Stone et al., 2021). The implementation of these concentrated loads produces residual training effects that can be carried over into the next block, a concept known as phase potentiation (Issurin, 2009; Stone et al., 2006; Stone et al., 2021).

Block periodization is comprised of stages of training that include three periodization blocks; the accumulation (general preparation), transmutation (special preparation), and realization (competition) blocks (Issurin, 2008; DeWeese et al., 2015; Stone et al., 2021). Each stage involves differing lengths of each block, such that the accumulation and transmutation phases are larger and the realization phase smaller across a stage. Early stages generally have relatively long accumulation and transmutation phases. However, as the target competition approaches, stages will favor smaller accumulation and transmutation phases while spending more time in the realization phase (Issurin, 2008).

The first periodization block is termed an accumulation and is typically characterized by higher training volumes, lower intensities, and relatively low mechanical specificity. During this time, the intention is to raise sport specific fitness, including aspects such as body composition alterations and increasing work capacity (DeWeese et al., 2015; Stone et al., 2021). The second block, transmutation, is typically characterized by moderately high volumes (typically not as high as the accumulation phase), low to moderate intensities, and higher mechanical specificity. This block is useful for transitioning athletes from higher volume, less specific training experienced during accumulation to higher intensity, very specific training that more closely resembles competition (DeWeese et al., 2015; Stone et al., 2021). The final block of training before competition is the realization and is typically characterized by moderate to low volumes of training with moderate to high intensities that are mechanically specific to performance. The purpose of this phase is to maintain fitness as much as possible, while enhancing technical consistency/efficiency and lowering accumulated fatigue (DeWeese et al., 2015; Stone et al., 2021). Lastly, transition phases of active rest are used to provide the athlete time to recover physically and mentally from training and competition (Bompa & Haff, 2009; Nàdori & Granek, 1989). Overall, for the strength-power athlete, Stone et al. (1981) suggested a periodized model aimed at developing hypertrophy, max strength, strength, and power, and then peaking in that order to drive performance, which has since been supported by the literature (Minetti, 2002; Zamparo et al., 2002).

Characteristics of the Sport of Weightlifting

Weightlifting is a strength-power sport within which athletes operate in a spectrum of bodyweight classes to compete. Competition is decided based on lifting the highest total amount of weight in the snatch and clean and jerk. In the snatch, the first lift in competition, the lifter attempts to lift the barbell from the floor directly to the overhead position in one swift motion. In the second lift, the clean and jerk, the lifter attempts to lift the barbell from the floor to the shoulders (clean), and then from the shoulder to overhead (jerk). Both lifts are completed when the lifter controls the barbell overhead with locked arms, feet aligned, and standing completely erect. Each lifter is provided with three attempts per lift, with the heaviest weight lifted in both the clean and jerk and snatch used for calculating that athlete’s total. The lifter with the highest total in each bodyweight class is declared the winner. To increase the odds of winning, the development of strength, rate of force development (RFD), power, and high-intensity exercise endurance should be the primary emphasis when training weightlifters (Stone et al., 2006). Weightlifting programming warrants the use of periodized resistance training in which programming strategies include both the competition lifts and accessory movements such as squats, presses, pulls, and derivatives of the competitive lifts. Although success in weightlifting involves a combination of explosive strength, technique, and flexibility (Enoka, 1979; Garhammer, 1989), the main determinant between non-elite and elite lifters seems to be influenced by force production capabilities (Kauhanen et al., 1994, Cunanen et al., 2020; Suarez, 2022).

Kinetics

In order to move the bar, the lifter must apply sufficient force to it (Baumann et al., 1988). The weightlifter's ability to perform is primarily driven by the strength and power of the hips and legs (Garhammer, 1980). This is observed when examining the well-developed lower bodies of trained weightlifters compared to other athletes of similar size. Indeed, when both Garhammer (1980) and Stone, O'Bryant, Williams, Johnson, and Pierce (1998) observed the kinetic differences between successful and unsuccessful lifts, they discovered that successful snatch attempts depended largely on the magnitude and RFD produced by the lifter. Furthermore, when comparing Finnish elite and district level weightlifters, Kauhanen, Hakkinen, and Komi (1984) observed strong correlations between relative ground reaction forces during the pull and weightlifting performance. They (Kauhanen et al., 1984) indicated that the primary difference between the elite lifters and district level was force production capabilities and not technique, a finding corroborated by Cunanan et al. (2020) and Suarez et al. (2022). In the competition lifts, weightlifters must generate very high peak forces, power outputs, and RFD (Storey & Smith, 2012), indicating that the ability to produce force (and quickly) appears to be an important determinant of elite weightlifting performance.

Strength

Although tactical training is an integral part of weightlifting, it stands to reason that since max strength strongly influences weightlifting performance, and technique often stabilizes after a few months to years of training, prioritizing strength training is more beneficial than technique training with advanced weightlifters (Stone et al., 2005). Indeed, except for the drop under phase of the jerk, Kauhanen et al. (1984) found no significant kinematic differences between non-elite and elite lifters, which can be explained by the observation that technique tends to be relatively stable in a relatively short period of weightlifting training. Interestingly, this idea is supported by Garhammer (1993), who observed minimal changes in lifter and bar kinematics across several years while the weight lifted and power output increase ~10-20%. Consequently, since the major contributing factor to elite weightlifting performance is likely peak power production, and peak power is significantly influenced by force production, max strength should be the primary focus of weightlifting training (Stone et al., 2005). In the early development of a weightlifter, training technique is undoubtedly important, but as a lifter advances, it will likely be more beneficial to emphasize development of max strength to improve performance, rather than technique.

Physical and Physiological Characteristics

Due to the nature of weightlifting, many elite weightlifters, within the same weight class, possess similar characteristics of height, weight, body composition, and relative limb lengths (Stone & Kirksey, 2000). Male weightlifters in the light to middle-weight weight classes (i.e., 56kg-85kg) tend to have body fat percentages around 5-10% and share similar body composition characteristics to jumpers, sprinters, and wrestlers of similar weight. Conversely, weightlifters in heavier weight classes (94kg-105+kg) can have body fat percentages ≥17% and similar body compositions to heavyweight wrestlers, throwers, and powerlifters (Storey & Smith, 2012). Weightlifters generally try to maximize the amount of muscle they can carry within their weight class, which often results in weightlifters being shorter and possessing higher relative body masses compared to other athletes. Consequently, they tend to have proportionally shorter arm spans and tibia lengths, and relatively long torsos (Carter et al., 1982; Marchocka & Smuk, 1984). Indeed, such anthropometric characteristics provide mechanical advantages during the competitive lifts, as the mechanical torque required to lift a given load is less due to the shorter lengths of the lever arms, concomitantly reducing the work required due to the shorter distance that the barbell must be displaced vertically (Keogh et al., 2007). Additionally, shorter, leaner athletes can maximize muscle cross-sectional area (CSA) within their weight class, which has been demonstrated to be advantageous for performance (Ford et al., 2000).

Weightlifters have been found to possess a greater abundance and muscle CSA of type IIa fibers and a larger II:I muscle CSA than most other athletes because of the high force demands of their sport (Fry et al., 2003; Serrano et al., 2018). Both the size and content of type IIa fiber have been shown to correlate strongly with weightlifting performance (Fry et al., 2003; Serrano et al., 2018). Partly, due to these qualities, the contractile RFD and isometric peak force (IPF) of weightlifters have been reported to be ~13-16% and ~15-20% greater than in other strength and power athletes (Storey & Smith, 2012). During the competition lifts, weightlifters achieve peak force, power, and barbell velocities in less than 260 ms (Garhammer, 1991). Nevertheless, the second pull (thigh upward) is the primary propulsive phase of the lift and required extremely high forces to be rapidly generated in even less time during this period. Consequently, maximum contractile RFD is an important contributor to weightlifting performance. Taken together, training that maximizes both the size and amount of type II fibers and increases peak force, power, and RFD should be emphasized in the preparation of a weightlifter.

Hypertrophy

Within the discussion of skeletal muscle hypertrophy exists a substantial amount of ambiguity. Historically, within the context of resistance training, hypertrophy has been defined as an increase in muscle mass and CSA at the whole tissue and cellular level (Russell et al., 2000). However, due to the complex nature of muscle physiology and anatomy, as well as the measurement techniques used, Haun et al. (2019) proposed that hypertrophy be generally and simply defined as an increase in skeletal muscle size that is accompanied by an increase in protein, mineral, or substrate abundance (e.g., glycogen and intramuscular triglyceride). Nevertheless, hypertrophy is made more complicated by the fact that multiple intramuscular compartments can be augmented as a consequence of training, including connective tissue, myofibrillar, and sarcoplasmic domains. To monitor these different types of domains, different methods have been used to assess each, broadly at the whole-body, localized, microscopic, and ultramicroscopic and molecular level (Haun et al., 2019). Each of these measurements provides a different analysis, sometimes markedly, of skeletal muscle and therefore provides unique insights into hypertrophy.

Types of Hypertrophy

Although muscle protein synthesis (MPS) is often used a proxy for skeletal muscle hypertrophy, there are different sub-fractions of MPS that contribute to the increase in muscle size, namely myofibrillar and sarcoplasmic (reticular, mitochondrial, glycogen, and other sarcoplasmic constituents). The sub-fraction of MPS is important in relationship to the performance enhancement that will be attained by the athlete. Indeed, strength-power athletes benefit from the increase in the myofibrillar sub-fraction by increasing the total contractile tissue available and therefore force producing capabilities. Furthermore, the fiber type that expresses this increase in contractile capability also results in performance enhancement. Although still elusive, there are several potential mechanisms that result in the relative increase in each sub-fraction of MPS and are important considerations for driving the training process.

Myofibrillar. It appears that the majority of hypertrophy induced by long-term resistance training programs results from an increase of sarcomeres and myofibrils that are added in parallel (Paul & Rosenthal, 2002; Maden-Wilkinson et al., 2020; Tesch & Larsson, 1982). When subjected to overload, the myofibers and extracellular matrix in skeletal muscle are perturbed, setting off a chain of myogenic events that lead to an increase in the size and amount of myofibrillar contractile proteins actin and myosin, and the total number of sarcomeres in parallel (Schoenfeld et al., 2010). This augments the diameter of individual fibers, resulting in an increase in muscle CSA (Toigo & Boutellier, 2006) both of which have been strongly associated with an athlete's ability express max strength and power (McMahon et al., 2015). Beyond parallel increases in sarcomeres, which result in increases in force production (Lieber & Ward, 2011), sarcomeres may also increase serially in a given muscle length, adapting to a new functional length and increasing muscle fiber velocity (Lieber & Ward, 2011).

Sarcoplasmic. Interestingly, in contrast to myofibrillar hypertrophy, skeletal muscle hypertrophy may also be induced by an increase in its sarcoplasm, known as sarcoplasmic hypertrophy. This occurs when there's a disproportionate increase in the volume of sarcoplasm relative to myofibril protein accretion (Haun et al., 2019b; Vann et al., 2020b). This is thought to occur by an increase in sarcoplasmic constituents such as mitochondrial size and/or density, the sarcoplasmic reticulum, macromolecules (e.g., ribosomes, glycogen, and lipid droplets), and various proteins and enzymes. While several studies have reported increases in sarcoplasmic hypertrophy (Haun et al., 2019b; Meijer et al., 2015; Vann et al., 2020a), the literature on the topic is mixed (Roberts et al., 2020). Furthermore, tissue edema is associated with localized damage and manifests as a retention of both intracellular and interstitial fluid, and through exercise-induced muscle damage, can be accompanied by sarcolemma damage where an infiltration of large serum protein such as albumin and fluid occur within and around muscle fibers (Valle et al., 2013), and therefore might not be demonstrative of typical sarcoplasmic hypertrophy, but edema (Yu et al., 2013). Nevertheless, acute increases in protein synthesis in untrained populations do not correlate with eventual resistance training-induced muscle hypertrophy, and instead likely reflect muscle repair and remodeling due to damage (Damas et al., 2015; Damas et al., 2018, DeFreitas et al., 2011).

Potential Mechanisms of Hypertrophy

The drive to increase lean body mass is globally pursued by those that lift weights. Due to the strong correlation between muscle CSA and muscle strength (Maughan et al., 1983; Maden-Wilkinson, 2020), increased muscle mass is an important goal for athletes involved in strength and power sports such as weightlifting. The type of muscle hypertrophy that takes place is also important, whether myofibrillar or sarcoplasmic, or type I versus type II fibers. While there are several potential mechanisms that may drive hypertrophy, mechanical tension is the primary and most well-evidenced driver, while metabolite accumulation and exercise induced muscle damage may play a minor role.

Mechanical Tension. Mechanically induced tension produced by stretch and force generation is considered necessary for muscle growth, and the combination of these stimuli (tension, damage, and metabolism) may produce an additive effect (Goldspink, 2002; Hornberger & Chien, 2006; Vandenburgh, 1987). Indeed, mechanical overload increases muscle mass, while unloading results in atrophy (Goldberg et al., 1975), which appears largely controlled by the protein synthetic rate during the initiation of translation (Baar & Esser, 1999; Kimball et al., 2002). Tension associated with resistance training is believed to disturb the integrity of the cell, causing mechano-chemically transduced molecular and cellular responses in the muscle fiber and satellite cites (Toigo & Boutellier, 2006). These signals are likely transduced by mechanosensory proteins contained in the costamere and cytoskeleton, such as dystrophin, integrin and GPR56 (Schiaffino et al., 2021).

Mechanical signals generated by passive stretch or muscle contraction can be transmitted through two multiprotein complexes that span the plasma membrane and connect the extracellular matrix with the intracellular cytoskeleton: the dystrophin glycoprotein complex and integrin adhesion complex (Schiaffino et al., 2021). These structures exist in abundance at sites of lateral or longitudinal force transmission, the costameres and myotendinous junctions, and act as shock absorbers that stabilize the sarcolemma during contraction or stretch. They also serve as scaffolds for signaling proteins and are therefore may be involved in mediating a hypertrophic effect of contractile activity against high loads that occur during resistance exercise or passive stretch (Schiaffino et al., 2021). Indeed, downstream of mechanotransduction, the mTORC1 complex is activated, with mTORC1 being considered an important driver for protein synthesis (Deschenes et al., 1991; DeVol et al., 1990; Dunn et al., 1999; Dunn et al., 2000). However, the signaling pathways that link mechanical overload and mTOR activation during exercise induced muscle hypertrophy are still not completely clear (Schiaffino et al., 2021).

Metabolite Accumulation. Metabolite accumulation refers to the accumulation of metabolic byproducts such as those generated through anaerobic glycolysis for ATP production, including lactate, hydrogen ion, creatine, inorganic phosphate, and others (Suga et al., 2019; Tesch et al., 1986), as well as ischemia, which may produce an additive effect (Pierce et al., 2006; Toigo & Boutellier, 2006). Indeed, there are several studies that have reported an anabolic role of exercise induced metabolic stress (Rooney et al., 1994; Schott et al., 1995). These are theorized to occur through stress-induced mechanisms including alterations in cell swelling, hormonal milieu, free-radical production, and increased activity of growth-oriented transcription factors (Gordon et al., 1995; Goto et al., 2005; Takarada et al., 2000). It has also been hypothesized that the greater acidic environment that is produced by glycolytic training could lead to increased fiber degradations and stimulation of sympathetic nerve activity, possibly mediating an increased adaptive hypertrophic response (Buresh et al., 2009). However, although metabolite accumulation is often recommended for training to induce maximal hypertrophy (Krzysztofik et al., 2019), metabolite research generally indicates that metabolites are associated with muscle growth, rather than causative, and has not assessed the effects of metabolites independent of muscle contraction (Dankel et al., 2017). Ultimately, it is unclear what role metabolites play in hypertrophic outcomes and should be assessed independent of mechanical tension.

Exercise Induced Muscle Damage. Exercise training often results in localized damage to muscle tissue, which has been theorized to generate a hypertrophic response (Evans, 2002; Hill & Goldspink, 2003). This damage can be as small as a few macromolecules of tissue, or a result in large tears in the supportive connective tissue, basal lamina, and sarcolemma which induces injury to contractile elements and the cytoskeleton (Vierck et al., 2000). Since fibers within a fascicle can be of different lengths and the weakest sarcomeres are located in different regions of each myofibril, nonuniform lengthening can cause a shearing of myofibrils. Additionally, lengthening can result in the deformation of membranes, particularly T-tubules, leading to a disruption of calcium homeostasis and damage due to tearing of membranes and/or opening of stretch-activated channels (Allen et al., 2005). Once this damage is registered, macrophages infiltrate damaged fibers to remove cellular debris and maintain the fibers ultrastructure, producing cytokines that activate myoblasts, macrophages, and lymphocytes that are believed to lead to the release of growth factors that result in satellite cell proliferation and differentiation, promoting hypertrophy (Toigo & Boutellier, 2006; Vierck et al., 2000). Although there is a theoretical rationale as to how muscle damage may play a role in the hypertrophic response, there is not a direct cause-effect relationship that has been established (Schoenfeld et al., 2012). Indeed, the mechanism for damage control may be limited to cell repair rather than promoting additional hypertrophy.

Task Specific Hypertrophy

In contrast to maximal hypertrophy and the potential mechanisms that drive it, strength-power athletes such as weightlifters must be more methodical when it comes to training due to the importance of RFD, IM, and power. Due to weightlifting being a weight class sport, in order to maximize performance, weightlifters must avoid indiscriminate hypertrophy in specific muscles, portions of muscles, and fiber types (Travis et al., 2020).

For the past several decades, Henneman's Size Principle (Duchateau & Enoka, 2011; Henneman & Olson, 1965) has been used to understand the orderly recruitment of motor units (MU). In order to activate an appropriate set of MU's (the motor neuron and all the muscle fibers it innervates), the nervous system must "know" about the physiological and biomechanical properties of the muscle that could be used to perform the action (Enoka & Duchateau, 2019). The key properties of muscle that the nervous system must consider include its force capacity, direction and rate of force generation capacity, and how long the desired force can be sustained. Additionally, monosynaptic reflexes, such as the stretch shortening cycle, which occurs in pulling motions and the jerk, can facilitate the direction, magnitude, and rate of force generation.

To produce muscle force and power (force x velocity), recruitment of MUs in the brain stem and spinal cord must be stimulated by higher brain centers (Gordon et al., 2004). These alpha motor neurons send an activation signal from the nervous system to the muscle, innervating from a few tens to a few thousands of muscle fibers (Enoka & Duchateau, 2019). Once the alpha motor neuron is excited, an action potential travels down the axon to the axon terminal where acetylcholine is subsequently released into the neuromuscular junction, propagating the signal from the nerve to the muscle to stimulate contraction (Kuo & Ehrlich, 2015).

Fiber types are largely determined by the motor neuron type innervating the fiber. The motor neurons, leaving the spinal cord, that innervate a muscle are arranged in a longitudinal cluster known as a motor nucleus or motor neuron pool (Burke et al., 1977; Routal & Pal, 1999). Although muscle fibers are usually characterized as either type I, type IIa, or type IIx, there are likely subtypes, as a substantial number of fibers contain more than one MHC isoform (Bottinelli et al., 1996; Serrano et al., 2019). The proportions of pure and hybrid fibers change with age (Purves-Smith et al., 2014), and there's considerable overlap in the contractile properties of different fiber types. Indeed, muscle fibers can coexpress combinations of MHC isoforms, such as type I and IIa, or IIa and IIx hybrids (Bottinelli, 2001; Serrano et al., 2019), and these hybrid fibers can be "shifted" into fibers with considerably less hybridization through training (Kohnet al., 2007; Serrano et al., 2019; Williamson et al., 2001).

The force exerted by a muscle depends on both the number of MU's recruited into action and the rates at which they discharge action potentials (Duchateau & Enoka, 2011). MUs are recruited in an orderly sequence (Denn-Brown & Pennybacker, 1938) that depends on the differences in motor neuron size (Henneman, 1957; Henneman et al., 1965) and in order of increasing peak twitch force (Calancie & Bawa, 1985; Carpentier et al., 2001). Indeed, MU's have recruitment thresholds (Stein et al., 2005), and MUs with higher recruitment threshold tend to have faster contraction times than those with lower recruitment thresholds (Milner-Brown et al, 1973b). When a motor nucleus receives excitatory synaptic input, the depolarization of the membrane potential toward threshold is greatest in the small motor neurons due to their greater input conductance (Ohm's Law). The smallest MU's have the lowest threshold for excitation and innervate the slowest muscle fibers, while the larger, faster MUs are sequentially recruited as the stimulus strength increases (Wakeling et al., 2006). The last MUs recruited during a progressive increase in muscle force differs across muscles, ranging from approximately 60% to 85% of max force production (Enoka & Duchateau, 2019). Thus, generally, any increase in force beyond the upper limit of MU recruitment depends solely on the discharge rate. However, of importance for weightlifting, the rate at which MU are recruited is a primary determinate of the rate of force development, particularly in ballistic movements (Diderikson et al., 2020).

The ratio that expresses the number of muscle fibers innervated by a single motor axon is termed the *innervation ratio.* The average innervation ratio ranges from 5 to 10 in smaller muscles like the rectus lateralis and tensor tympani (Blevins, 1967; Carlsoo, 1958), and up to approximately 2000 for large limb muscles such as the medial gastrocnemius (Feinstein et al., 1955: Karpati et al., 2010). Because the peak force that a MU can produce depends on its innervation number, MU force varies exponentially across a given MU pool (Enoka & Duchateau, 2019). Indeed, whenever MUs are activated by the nervous system, muscle force does not increase linearly with the number of MU's activated. Indeed, glycogen depletion studies indicate that the innervation number varies within a MU pool, with lower-threshold MU's containing lower values (Bodine et al., 1987; Kanda & Hashizume, 1992). Muscles are comprised of both small, low force MU's and larger, high force MU's. Interestingly, the frequency distribution of innervation numbers within a MU is typically represented by an exponential function, rather than a linear relationship between innervation number and MU size (Elek et al., 1992; Kernell, 1992). For example, Enoka and Fuglevand (2001) found that 50% of the total number of fibers in a hand muscle (n = 44,000) were innervated by 102 out of the 120 MUs in the pool, with the remaining 18 MU's accounting for the remaining 50%. Therefore, muscle force does not increase linearly with the number of activated motor units, and this phenomenon likely depends upon the size and type of MU.

Two basic mechanisms result in the recruitment of larger, faster twitch MU: higher intensities and fatigue. Motor units are distinguished based on a recruitment threshold force (Heckman & Enoka, 2012); however, where this force lies is a matter of controversy. Some authors have reported full recruitment of the MU pool by training to failure at 30% 1RM (Carpinelli, 2008). However, other researchers have indicated that in order to fully activate higher threshold motor units, this cannot be accomplished by training to failure and suggest that in order to specifically target fibers with higher threshold MU's, higher loads (≥80% 1RM) and ballistic training may be warranted (Frobose et al., 1993; Fry, 2004; Mangine et al., 2015; Looney et al., 2016; Wallace & Janz, 2009), especially in the context of strength and power athletes where task specificity is important for hypertrophy and strength (Jenkins et al., 2017; Travis et al., 2020). Indeed, recent work by Miller, Lippman, Trevino, and Herda (2020) demonstrated that moderate-intensity contractions taken to fatigue did not recruit the entire pool of MU's, whereas higher intensity contractions not taken to fatigue resulted in greater neural drive and MU recruitment. Additionally, high power movements also result in the recruitment of type II MU's (Frobose, 1993; Macaluso et al., 2012).

Based on cross-sectional results among strength-power athletes that train in different manners, training at lower versus higher intensities has been found to result in decreased peak power and a reduction in specific tension (Meijer et al., 2015). Conversely, fatigue-induced changes in the force capacity of low-threshold MUs reduces the recruitment threshold of all larger MU's, despite minimal involvement in the task. This is the rationale for lower load training performed to muscular failure, since lower-threshold MU's will be recruited first, followed sequentially by higher threshold MUs as the lower MU's become fatigued (Burd et al., 2008). Although a recent meta-analysis found comparable hypertrophy between high and low loads, there was a trend towards high load producing slightly greater gains than low loads (Schoenfeld et al., 2017). Nevertheless, lighter loads show relatively greater increases in type I muscle fiber growth than type II fibers (Carroll et al., 2019b; Netreba et al., 2007), functionally reducing the II:I muscle CSA ratio. Ultimately, training with higher intensities facilitate, adequate recruitment of the MU pool (Enoka & Duchateau, 2019), greater increases in strength gain than lower intensities (Jenkins et al., 2017), prevent reductions in fiber specific tension (Meijer et al., 2015), improve the II:I muscle CSA ratio, and are recommended for strength and power athletes (Travis et al., 2020; Stone et al., 2021).

Although motor unit recruitment influences the magnitude of force and power development, enhanced rate coding is essential for rate of force and power development (Duchateau & Baudry, 2014; Kraemer & Looney, 2012). At relatively low forces, and especially during fast contractions involving high instantaneous discharge rates, the control of muscle force depends primarily on rate coding (Desmedt & Godaux, 1977; Enoka & Duchateau, 2017). Indeed, most MUs in a muscle are recruited with a load as low as 40% 1RM during ballistic contractions (Enoka & Duchateau, 2019). This rapid increase in force production occurs due to an increase in rate coding and can change in response to training. For example, 12 weeks of training with ballistic contractions involving moderate load with the dorsiflexor muscles markedly increased the instantaneous discharge rate of MUs in the tibialis anterior and was associated with an 82% increase in the rate of torque developed during ballistic isometric contractions (Van Cutsem et al., 1998). Interestingly, although the recruitment of MU's during voluntary contractions occurs in an order consistent with the size principle, it has been suggested that rapid contractions might involve preferential recruitment of fast-contracting motor units (Grimby & Hannerz, 1977; Wallace & Janz, 2009). However, it is unclear whether this occurs (Desmedt & Godaux, 1977b).

Beyond the upper motor neurons in the brain, alpha motor neurons (and interneurons) can also receive input from sensory neurons from the periphery that mediate important motor reflexes operating at the level of the spinal cord with or without upper motor neuron influence (Purves et al., 2004). At the muscular level, mechanoreceptors, known as muscle spindles, can also augment power (Kraemer & Looney, 2012) and work synergistically with ballistic movements. When compared to near maximum and maximum eccentric actions, concentric muscle actions produce substantially less force (Hoffman, 2012). However, when an eccentric muscle action is completed immediately prior to a concentric muscle action, the elastic properties of the muscle, through the stretch-shortening cycle (SSC), can be taken advantage of (Newton et al., 1997). This elastic component of muscle, consisting of the connective tissue surrounding each organizational layer of muscle tissue, allows the muscle to be stretched (Kraemer & Looney, 2012). When a muscle is stretched, muscle spindles rapidly contract to prevent potential tissue damage (Kraemer & Looney, 2012). These muscle spindles use Ia afferent sensory fibers to form monosynaptic excitatory connections with the alpha motor neurons in the spinal cord that innervate the same muscle, leading to rapid and efficient responses to changes in muscle length or tension (Purves et al., 2004). Ultimately, the utility of this reflex is understood when synchronized with a concentric muscle action because it augments power. This can be observed when a maximum effort squat jump with no SSC is compared with a maximum effort vertical jump utilizing the SSC (Kraemer & Looney, 2012).

In conclusion, several key factors result in the differential targeting of fiber types via resistance training. According to Henneman's size principle, MUs are recruited on the basis of size, with smaller, less forceful MU's being recruited before larger, more forceful MU's (Henneman & Olson, 1965). This force differential is partly due to differences in innervation ratio (Bodine et al., 1987; Kanda & Hashizume, 1992). Although training with lower intensities taken to failure may result in the recruitment of most of the MU pool (due to a decrease in recruitment threshold of faster MU's), this results in greater hypertrophy of type I fibers, likely as a result of type II fibers fatiguing and dropping out at a faster rate than type I fibers (Minigalin et al., 2015; Netreba et al., 2007; Vinogradova et al., 2013). Conversely, higher intensities (≥80% 1RM) facilitate adequate recruitment of the MU pool (Enoka & Duchateau, 2019), greater increases in neural strength gain than lower intensities (Jenkins et al., 2017), prevent reductions in fiber specific tension (Meijer et al., 2015), improve the 2:1 ratio, and are recommended for strength and power athletes (Travis et al., 2020). Additionally, ballistic training results in recruitment of most of the MU's in a muscle with a load as low as 40% 1RM (Enoka & Duchateau, 2019), rapidly increasing force production due to rate coding (Duchateau & Baudry, 2014; Kraemer & Looney, 2012), is augmented by the stretch reflex (Kraemer & Looney, 2012), and can be improved with training (Van Cutsem et al., 1998), and primarily targets type II MU's (Frobose et al., 1993; Wallace & Janz, 2009).

Muscle Memory

Skeletal muscle fibers are large multinucleated cells, that contain hundreds to thousands of nuclei (Snijders et al., 2020). Theoretically, the muscle fiber is divided into evenly distributed compartments, each under the control of a single myonucleus, and according to the myonuclear domain theory, each nucleus has a limited transcriptional capacity, only able to create proteins for use in the immediate area around the nucleus (Schwartz et al., 2016; Lee et al., 2018). As athlete's muscle hypertrophies, the ability of the myonuclei to regulate protein synthesis for a given area in the muscle becomes challenged due to the muscle's expansion. To combat this, satellite cells activated during training can be donated to the muscle as myonuclei, increasing the muscles number of myonuclei and maintaining and expanding the "myonuclear domain".

Interestingly, is has been hypothesized that myonuclei that have been added to support skeletal muscle hypertrophy are not lost with atrophy (Gantier et al., 2011; McCarthy & Esser, 2007). If true, this could act as a mechanism allowing muscle fibers to grow more expediently during retraining due to the magnitude of myonuclei remaining in an elevated state (Snidjers et al., 2020), a phenomenon known as muscle memory (Murach et al., 2018). Indeed, a positive linear, as well as logarithmic, relationship exists between myonuclear content and muscle fiber size, as well as myonuclear domain and muscle fiber size in humans (Snidjers et al., 2020).

In addition to the theoretical myonuclear domain theory, the expedience of retraining may be due to epigenetic changes such as muscle specific miRNAs (Murach et al., 2020), DNA hypomethylation (Seaborne et al., 2018). Hypomethylation generally promotes an enhancement in gene expression due to the removal of methyl groups from DNA, permitting improved access of the transcriptional machinery and RNA polymerases that allow transcription (Snidjers et al., 2020). Thus, training leads to an enhanced hypomethylated state of genes, which is maintained during detraining, and, upon retraining, enables greater transcription of these genes, allowing an enhanced muscle fiber growth response (Snidjers et al., 2020).

Although this area of research is still in its infancy, novel insights have been found, demonstrating a possible interplay of myonuclear accretion and epigenetic alterations. Indeed, Murach et al. (2022) found that, 1) after training, epigenetic profiles appeared distinct, likely to the contribution of satellite cell fusion from training; 2) resident myonuclei appear to be oriented towards anabolic and catabolic processes, with these nuclei being principal drivers of hypertrophic processes (Wen et al., 2021; Murach et al., 2021), whereas myonuclei derived from satellite cells may be epigenetically programmed for transcription factor regulation and cell to cell communication; 3) promoter CpG methylation might be related to transcription of ribosomal proteins; 4) myonuclei derived from satellite cells may support growth processes by contributing ribosomal macromolecular components to muscle fibers; and 5) the satellite cell derived myonuclei acquired from training might have a methylation memory of their pre-myonuclear identity. Moving forward, more research should be geared towards elucidating the interplay between myonuclear accretion, epigenetic alterations, and the role of native versus satellite cell derived myonuclei in the hypertrophic response.

Monitoring Training Adaptations for Weightlifting

Unlike many other strength-power sports, weightlifting has a minimal number of competitions throughout the year. This infrequent competition schedule increases the need for coaches to understand the timelines and magnitudes of adaptation that occur from different training stimuli, such as that described earlier through block periodization. As a result, weightlifting coaches could benefit from athlete monitoring programs that produce objective feedback concerning the adaptations that take place through each stage and block. As weightlifters' performance relies heavily on the ability to generate high forces within specific time intervals (Kipp et al., 2012; Stone et al., 1998; Suarez et al., 2019), the monitoring of specific kinetic adaptations to training is warranted.

Isometric Mid-Thigh Pull

One-repetition maximum (1RM) tests have been a common procedure used to assess the ability to produce force in strength-power sports (Buckner et al., 2017), as strength is an important contributor to sport performance (Suchomel et al., 2016). Although it seems natural to employ these tests with weightlifters, due to the nature of their sport, 1RMs inevitably produce fatigue and can therefore affect training. However, an alternative means to monitor strength variables is through isometric tests, which confer the advantage of being minimally fatiguing and relative quick and safe. Although different tests have been developed throughout time (Verkhoshansky, Y. & Verkhoshansky, 2011), a test known as the IMTP was developed (Stone et al., 2019) and first discussed in the literature by Haff et al. (1997) and has since become one of the most frequently used tools for athlete monitoring for both academic research and athletic programs since.

The IMTP enables comparison of force-time curve characteristics between isometric and dynamic tasks and is performed standing on force plates in a rack that permits bar height adjustment. Although there can be minor individual variation in posture, the ideal pulling position should imitate the second pull in weightlifting. This position typically consists of an erect torso, straightened arms, knee angles between 120-135 degrees, hip angles between 140-150 degrees, and feet flat on the floor (Beckham et al., 2018; Comfort et al., 2019; Kraska et al., 2009). In this position, athletes strive to produce force vertically on the force plates by pulling as fast and hard as possible. Through force trace measurements during these trials, variables such as impulse, RFD, and force can be acquired, each of which can provide insights into an athlete's acute kinetic abilities (Beckham et al., 2013; Haff et al., 2005), or feedback into training adaptations if examined longitudinally (Hornsby et al., 2017).

Associations to Weightlifting Performance. In the IMTP, the pulling position is designed to imitate the power position of the clean (Haff et al., 1997) and is used to measure variables such as RFD and peak force (PF) that correlate strongly to weightlifting performance (Beckham et al., 2013; Hornsby et al., 2017). Indeed, the highest power outputs and velocities can be generated from the power position into the second pull of the clean and snatch as a result of the superior ability to produce force in this position (Baumann et al., 1988; Beckham et al., 2013; Gourgoulis et al., 2002). These observations demonstrate the power position's importance for weightlifters and other athletes using weightlifting movements. Moreover, RFD and max strength are exceedingly important attributes to weightlifting performance. Consequently, the IMTP is an extremely useful monitoring tool for performance as it allows coaches and lifters to safely measure important variables in a sport specific position, independent of performing 1RM's.

Peak Force. Peak force is the most frequently measured variable from IMTP tests, with strong correlations having been observed between PF and lower body 1RM's (Mcguigan et al., 2010; McGuigan & Winchester, 2008), dynamic mid-thigh pulls (Haff et al., 1997), and weightlifting performance (Hornsby et al., 2017). Indeed, very strong correlations (r=0.830-0.838) have been observed between absolute PF values and weightlifting competition performance in twelve novice to advanced weightlifters (Beckham et al., 2013). Beyond using PF to assess weightlifting performance, several researchers have used PF to track maximum strength abilities throughout training phases in weightlifters (Hornsby et al., 2017; Suarez et al., 2019). Additionally, PF appears to be relatively stable in well-trained strength athletes and is only considerably affected when accumulative fatigue is severe (Hornsby et al., 2017; Norris, Joyce, Siegler, Clock, & Lovell, 2018). Because PF is relatively insensitive to fatigue and has been reported to have very high between and within session reliability (Brady et al., 2018; Guppy et al., 2018; Haff et al., 2005; Kraska et al., 2009; Stone et al., 2003), it is a logical variable to consider for assessment of long-term changes in max force production.

Rate of Force Development. Although the ability to produce force is of profound importance for sport performance, most sports require force to be developed within a certain time frame. Consequently, developing force quickly may be the most important goal of the training process (Taber et al., 2016). Indeed, this idea has been supported by several investigations of the relationships between RFD and sports skills such as jumping, throwing, sprinting, change of direction ability, and weightlifting performance (Beckham et al., 2013; Haff et al., 2005; Stone et al., 2003; Wang et al., 2016; Zaras et al., 2016). Beyond athletic performance, RFD has been found to be a sensitive, indirect marker of muscle damage (Crameri et al., 2007; Farup et al., 2016; Peñailillo et al., 2015), neuromuscular fatigue (Rodríguez-Rosell et al., 2017; Thorlund et al., 2008), and fiber type (Andersen et al., 2010; Häkkinen et al., 1984; Viitasalo et al., 1981; Viitasalo & Komi, 1978), and is considered to be highly related to most sport-specific tasks, displaying a greater sensitivity to changes in neuromuscular function (Maffiuletti et al., 2016), making it an effective tool for monitoring.

RFD is calculated by dividing the change in force by change in time. Using specific time bands to calculate RFD has demonstrated high reliability than quantifying peak RFD values alone (Haff et al., 2015), with several time band having been suggested to be governed by different physiological mechanisms based on the time frame (Andersen & Aagaard, 2006; Andersen et al., 2010; Waugh et al., 2013). Indeed, different time bands may respond differently to various training stimuli as a consequence (Rodríguez-Rosell et al., 2017). Specifically, the earlier time bands (<100ms) may be influenced more greatly by neural drive and intrinsic muscle properties (Andersen et al., 2010; Gruber & Gollhofer, 2004; Van Cutsem et al., 1998), while later time bands (≥150ms) are more closely related to maximum muscle size and particularly maximum strength (Folland et al., 2014; Kavvoura et al., 2018; Rodríguez-Rosell et al., 2017).

Although monitoring both early and late RFD time bands can provide a more comprehensive understanding of training process related adaptations, as maximum strength is less effected by training volume reductions, for an athlete returning from injury, the later time bands may be less affected by detraining (Gondin et al., 2006).

Jump Performance

In most sports, jumping is a common task. Vertical jump performance if often used as an indirect measurement of both an athlete's explosive ability and competitive readiness, with the squat jump (SJ) and countermovement jump (CMJ) both having been used with various athletes across a competitive season to monitor the training response (Freitas et al., 2014; Gibson et al., 2016). During the competition phase, monitoring jump performance could provide an effective way to determine an athlete's response to training without causing undue fatigue. Furthermore, it has been shown to be discriminant between training level (collegiate, sub-elite, elite) in a variety of sports including weightlifting (Carlock et al., 2004), volleyball (Pion et al., 2015), and sprinting (Peterson, Alvar, & Rhea, 2006). Indeed, both jump types are often used to detect fluctuations in power output, jump height, and dynamic RFD capabilities throughout the training cycles leading up to competition. In fact, they are a preferred monitoring tool when assessing weightlifting competition preparedness due to their limited interference with training, as well as biomechanical similarity to weightlifting activities (Garhammer, 1980; Garhammer & Gregor, 1992). Moreover, peak power and jump height are purportedly higher in weightlifters when compared to other athletes (Funato et al., 2000; Garhammer, 1980; Hackett et al., 2016; McBride et al., 1999; Stone et al., 2003; Teo et al., 2016), with static jump specifically having been shown to be more strongly related to absolute and scaled weightlifting performance in male and female weightlifters (Carlock et al., 2004; Travis et al., 2017). Consequently, assessing changes in jumping performance throughout a stage of training could provide an indirect measure of performance changes.

Ultrasonography

Monitoring changes in muscle architecture can be useful to deduce alterations in force production capacity, contraction velocity, muscle function, and hypertrophy from training. Although magnetic resonance imaging (MRI) is considered the “gold” standard for muscle architecture assessment (Stokes et al., 2021), it is not an instrument that is widely accessible to coaches and athletes. Fortunately, ultrasonography, a potential lower-cost, fast, non-invasive, and readily available alternative to the MRI (Scanlon et al., 2014; Stokes et al., 2021), has become prominent in recent years, and has been shown to be a valid and reliable method of assessing muscle size and architecture (Hides et al., 1995; Palmer et al., 2015; Raadsheer et al., 1994). Indeed, US has been used to assess measures of muscle morphology, such as muscle CSA, of the vastus lateralis in athletic populations (Bazyler et al., 2017; Nimphius et al., 2012; Zaras et al., 2016). Moreover, several studies using the ultrasound as a longitudinal athlete monitoring tool have observed relationships between muscle alterations and specific performance variables (Bazyler et al., 2017; Nimphius et al., 2012; Zaras et al., 2016). Additionally, Wagle et al. (2017) demonstrated that the subject’s position when measured (i.e., lying vs standing) affected the relationships between the measurements taken and performance variables. Indeed, the vastus lateralis is usually considered to be the largest and most powerful section of the quadriceps, particularly in athletes (Secomb et al., 2015), and its muscle CSA has been shown to be a strong performance indicator for movements often used by weightlifters such as vertical jumps, IMTP, squat, and weightlifting movements (Bazyler et al., 2018; Brechue & Abe, 2002; McMahon et al., 2015; Secomb et al., 2015; Zaras et al., 2016). US has become a common measurement for monitoring by sport scientists.

Muscle Size

In athletes, the vastus lateralis is usually considered to be the largest and most powerful section of the quadriceps (Secomb et al., 2015), and its muscle CSA is often measured using ultrasonography. Ultrasonography can quantify an entire section of muscle through a panoramic sweep, allowing regional changes of the muscle to be quantified (Franchi et al., 2017; Mangine et al., 2018). Vastus lateralis muscle CSA has been shown to have strong relationships to movements commonly used by weightlifters such as IMTP's, vertical jumps, deadlift, back squat, and power cleans (Bazyler et al., 2018; Brechue & Abe, 2002; McMahon et al., 2015; Secomb et al., 2015; Zaras et al., 2016). Although the vastus lateralis shows some variability depending upon the biopsy site, it appears to be composed of approximately 53% to 65% fast-twitch muscle fibers (Clarkson et al., 1980; Horworth et al., 2021), and is useful in providing insight into the relationship between performance and changes in lower extremity musculature (Fry et al., 2003). Indeed, it has been suggested that increases in maximum strength increase linearly with increases in muscle CSA, which is a vital quality for strength-power athlete's competition demands (Scanlon et al., 2014).

Isometric peak force and isometric peak force allometrically scaled (IPFa), as measured by the IMTP, is strongly related to weightlifting performance and other dynamic muscle actions (Stone et al., 2005; Stone et al., 2019). Additionally, beyond IPF, rate of force development between 200-250ms is affected by several morphological factors including muscle thickness, pennation angle, tendon properties, and muscle fiber type (Haff et al., 2005; Kauhanen et al., 2000; Stone et al., 2005). Indeed, a larger anatomical pennation angle allows more sarcomeres to be stored in parallel (Stebbings, 2015) and, as a result, increases in muscle CSA are strongly associated with max strength and power (McMahon et al., 2015). Theoretically, these increases would result in improvements in isometric RFD (Storey et al., 2012) and are worth monitoring throughout the training process to use as a surrogate measure of performance related changes.

Body Composition

An effective and low-cost method to investigate changes in body composition is through the estimate from the sum of 7 skinfold sites (tricep, subscapular, mid-axillary, supraspinale, chest, abdominal, quadricep) using a skinfold caliper (Ball et al., 2004). Although many alternatives to assess body composition exist, such as hydro-densitometry, air displacement plethysmography, dual-exergy x-ray absorptiometry (DXA), and more, skinfolds are considered one of the most efficacious methods to assess fat free mass and track changes over time in the applied sport setting (Kasper et al., 2021). Indeed, it is least affected by everyday activities such as ingestion of a meal and changes in hydration status (Kerr et al., 2017; Norton et al., 2000), and has a high degree of agreement with whole-body measures from DXA (Doran et al., 2013).

Summary

The development of weightlifters should emphasize maximizing strength and RFD abilities, increasing and maintaining muscle CSA, especially of type II muscle fibers through task specific hypertrophy, and sequencing training to achieve a peak in performance at the competition. During the training process, myonuclear accretion and epigenetic changes occur to enhance the muscle protein synthetic response and oversee a greater amount of muscle mass. During detraining, which can occur volitionally or due to injury, changes in myonuclei and epigenetics may persist (muscle memory), enhancing the speed of the retraining process. Research monitoring kinetic and muscle morphological adaptations in weightlifters' post-injury following a block-periodized style of training is nonexistent. Thus, the purpose of the following observation is to retrospectively investigate 1) the efficacy using a block periodization-style rehabilitation training protocol, 2) the effectiveness of sport specific athlete monitoring to observe physiological adaptations, and 3) assess laboratory- and competition-based performance changes in a collegiate male weightlifter following a right knee meniscal injury.

Chapter 3. Return-To-The-Platform: The Case of a Collegiate Level Weightlifter Recovering from a Meniscus Injury

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ABSTRACT

The purpose of this study was to observe physiological metrics relative to training-induced adaptations in conjunction with laboratory- and competition-based performances in a super-heavyweight weightlifter recovering from a meniscus injury. A retrospective analysis was conducted on a collegiate level male weightlifter (23.2 yrs; 131.9 kg; 187.3 cm) over the course of 21-weeks post-meniscus surgery. Body mass, body fat percentage, hydration status, vastus lateralis muscle cross-sectional area, jump performance, and isometric midthigh pull were regularly assessed as part of an ongoing athlete monitoring program. Pre-injury baseline (T0) measurements were collected relative to a major national competition (COMP1). Post-injury measurements took place at the end of sequential training blocks: strength-endurance training block 1 (T1), basic strength block 2 (T2), and transmutation block 3 (T3). The final measurement session (T4) was conducted three-days post-local competition (COMP2). Only statistically significant increases were observed from T0-T4 for muscle CSA (p=0.0367), isometric peak force (p<0.05), isometric peak force allometrically scaled to body mass (p=0.0367), and rate of force development at 250ms (p=.0367). While non-significant changes were observed for jumping performance, jump height and net impulse did, however, return to baseline. Competition based performances also showed marked improvements from pre-to-post injury via an increase in weightlifting total (3.2%Δ, +9kg) and Sinclair score (1.8%Δ, +5.3au). Thus, based on these findings, implementing an evidence-based training program along with a sound athlete monitoring protocol can aid with reducing an athlete's return-to-train timeline while improving physiological, laboratory- and competition-based performance outcomes.

Key Words: Isometric Peak Force, Rate of Force Development, Jump Height, Net Impulse

INTRODUCTION

Weightlifting is a strength and power sport where lifters contest two events: a) snatch, which is performed in one motion from the ground to the overhead position, and b) clean and jerk, which is performed in two motions from the ground to the overhead position. The goal in competition is to lift a maximum weight in each event. Based on the highest loads achieved within each event, the lifters produce a weightlifting total (i.e., highest load for snatch + highest load for clean and jerk) to determine the winner within a given weight class. Additionally, a coefficient termed, Sinclair score, can be applied to each lifter's weightlifting total. This score is relative to body mass and used to determine best performances while obviating sex and weight class. The key in weightlifting is to steadily increase one's weightlifting total and Sinclair score over the course of an athletic career while minimizing injuries so that competition participation can be optimized.

Interestingly, despite the explosive movements involved, injuries in strength sports such as weightlifting, powerlifting, strongman, and throwing events occur less frequently than may be assumed (1,38). In fact, based on several reviews, as few as 0.017-3.3 injuries occur per 1,000 hours of training (1,22,30) for these sports. For additional context, in traditional sports such as American football, basketball, and soccer, injury risks are much higher occurring at 4.31-9.6 injuries per 1000 hours of training and play (24,38). Within strength sports, the bodily areas most susceptible to injury appear to be the knees, lower back, and shoulders (1,30). More specifically, in weightlifting, knee injuries have up to a 32% chance of occurring more frequently than others and is the most common injury within the sport (1,30). The knees could be prone to injury due to general wear and tear and the frequency at which weightlifters are required to perform deep squats when performing the competition movements, weightlifting derivates, back squat, and front squat training. However, it is unlikely, as these movements tend to reduce injury risk at the knee (20,23). However, fatigue, which can be caused by a number of factors such as insufficient sleep (27), nutrition (48), and non-functional overreaching and overtraining (11), can increase muscle's susceptibility to injury (31,33). According to Wang et al. (51) weightlifters have reported that their injuries were associated with tiredness and fatigue, technical errors, and continuous excessive loading. Thus, the use of programmed variation (e.g., heavy and light days) and the implementation of athlete monitoring to mitigate fatigue, reduce injury risks, manage heavy and light loading schemes while optimizing preparedness is warranted to increase the longevity of a lifter's career.

Unfortunately, the current literature regarding return-to-competition, rehabilitation, and re-injury prevention is lacking, particularly relative to strength sports. The existing protocols are often specific to injuries within non-strength-power sports (9,15), or provide information that is too broad referencing the need to monitor pain and swelling, limb range of motion, and psychological readiness (2). While most injuries that occur can be considered a higher- or lower-frequency injury occurrence within a given athlete population, researchers are often limited to incorporating case studies to aid with better understanding risks, restoration, and prevention. However, case studies generally fail to provide a comprehensive investigation that includes detailed information about a) specific training protocols used prior to, during, and after the injury, b) sport specific monitoring tools, and c) changes in competition performance before and after injury to demonstrate the efficacy of the training intervention. Thus, research investigating injuries in weightlifters (i.e., knee) are needed to provide practitioners with a rubric to guide rehabilitation of athletes.

Additionally, it is well known that block periodization can serve as a framework to sequentially produce desired training adaptations across various training phases (14,43). However, documenting the use of block periodization as a means of effective rehabilitation has not been produced within the current literature. It is also well accepted that using athlete monitoring tools such as observing muscle cross sectional area (CSA) via ultrasonography, jumping performance, and isometric maximal force tests can produce an intra-athlete performance profile to determine recovery-adaptation rates (4,25,46,47). Thus, the use of block periodization in conjunction with athlete monitoring could serve as a way to prevent injuries and rehabilitate lifters back to the platform.

Thus, the purpose of this observation was to retrospectively investigate 1) the efficacy using a block periodization-style rehabilitation training protocol, 2) the effectiveness of sport specific athlete monitoring to observe physiological adaptations, and 3) assess laboratory- and competition-based performance changes in a collegiate male weightlifter following a right knee meniscal injury.

METHODS

Experimental Approach to the Problem

This observation used a case-study approach to retrospectively monitor a collegiate level male weightlifter before and after suffering a right knee meniscus injury that required surgery. The measurements made were part of an ongoing athlete monitoring program. The data for this observation was collected over a 13-week period. The athlete had been competing in the super-heavyweight 109kg+ weight class for approximately 1 year. The observation began relative to his first competition (COMP1) as an ETSU team weightlifter whereas the second competition

(COMP2) took place at a local meet that was a by-product of his modified post-injury training regimen. A full battery testing protocol that consisted of various physiological and performance measurements was collected (baseline; T0) three days after COMP1. Approximately four weeks after T0, the athlete a right knee meniscus tear became apparent and required surgery, which took place an additional four weeks after the injury occurrence. After two-weeks of recovery, the athlete engaged in eight-weeks of reduced and modified training, followed by restoration of training for 13-weeks. Data collection occurred after each concentrated load training block via block 1 (T1), block 2 (T2), block 3 (T3), and ended with a post-competition measurement session (T4). Data for ultrasound and the isometric midthigh pull (IMTP) were collected at all time points, whereas the full battery of testing, including skinfolds and jump performance, were only collected at T0, T1, and T4. Data was collected at the same time of day within three days of the end of each block.

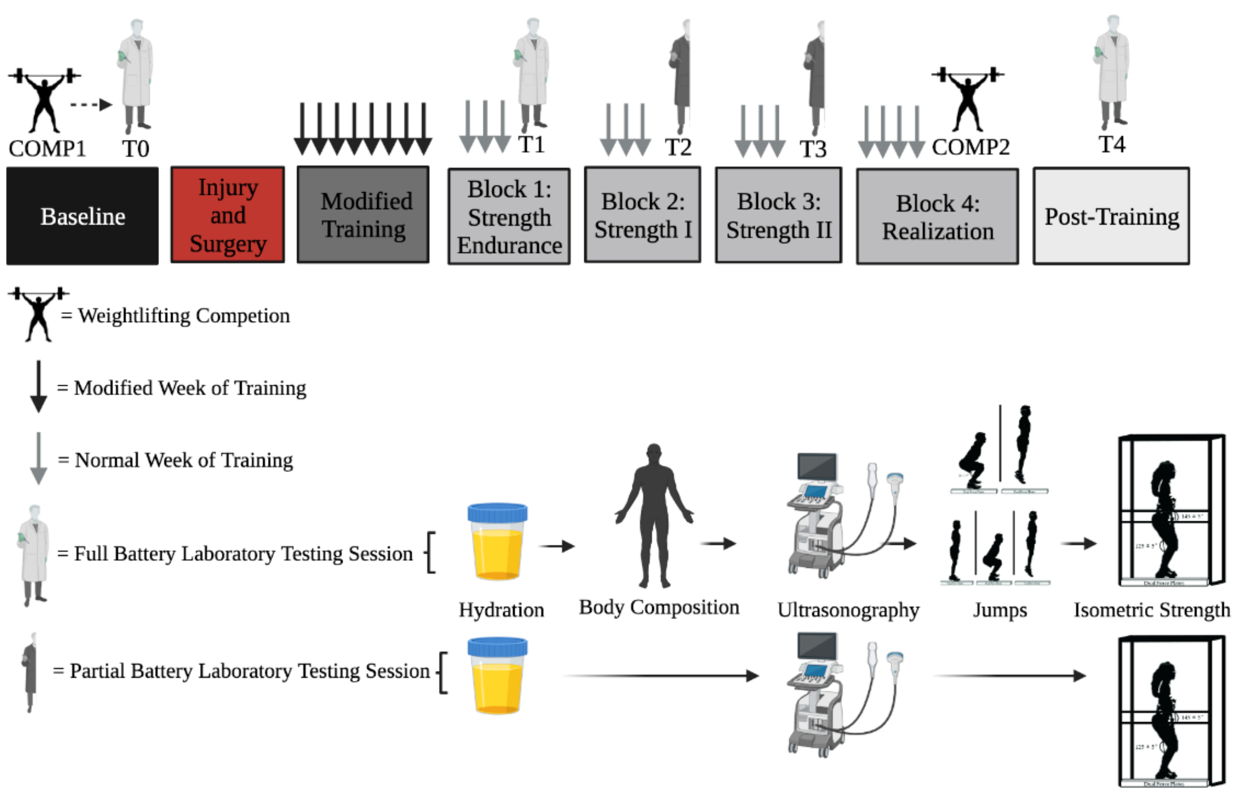

Figure 3.1. Study timeline and testing procedures. COMP1 = Competition 1, T0 = Pre-injury baseline, T1 = Strength-Endurance Block 1, T2 = Basic Strength Block 2, T3 = Strength Transmutation Block 3, COMP2 = Competition 2, T4 = Post-Competition 2 Testing.

Athlete Characteristics

We retrospectively monitored a super-heavyweight collegiate level male weightlifter (23.2 yrs; 131.9 kg; 187.3cm) before and after a meniscus injury. Before injury, the athlete had been an American collegiate football player prior to becoming a weightlifter. The athlete had a history of knee injury during American football. The athlete had competed in the 109kg+ weight class for approximately one year under USA Weightlifting sanctioned competitions. At T0 relative to COMP1, the lifter produced a 122 kg snatch, 160 kg clean and jerk, 282 kg weightlifting total, and a 289.62 Sinclair score.

Training

After surgery, the athlete completed a modified training regimen where volume was reduced and lifts were modified for a total of eight weeks, followed by 13-weeks using a block periodization (i.e., phase potentiation) model of training consisting of sequenced concentrated loads: T1 with a strength-endurance emphasis over three weeks; T2 with a basic strength emphasis over three weeks; T3 strength-power transmutation emphasis over three weeks; and a five week realization phase beginning with a 1 week overreach block and ending with COMP2 and a final testing at T4. Each training week consisted of twice daily training over Monday, Wednesday, and Friday, and ended with a single training session on Saturdays. See table 3.1 and 3.2 for training details.

Table 3.1 – Training Programming: Sets and Repetitions

Week	Testing	Block	Set x rep	Daily Intensities (M, W, Th, S)
	COMP1 T0			
Week 1-8		RMT		

Week 9			3x10	ML, ML, VL, VL
Week 10	T1	SE	3x10	M, M, VL, VL
Week 11			3x10	L, L, VL, VL
Week 12			3x5 (1x5)	M, M, L, VL
Week 13	T2	BS	3x5 (1x5)	MH, MH, L, L
Week 14			3x3 (1x5)	M, ML, VL, VL
Week 15			3x3 (1x5)	MH, MH, VL, VL
Week 16	T3	T	3x3 (1x5)	H, H, VL, VL
Week 17			3x3 (1x5)	ML, L, VL, VL
Week 18			5x5	M, M, VL, VL
Week 19			3x3 (1x5)	M, MH, VL, VL
Week 20			3x3 (1x5)	MH, M, VL, VL
Week 21	COMP2	R	3x3 (1x5)	ML, L, VL, Meet
Week 22	T4		3x3 (1x5)	L, SPEC, VL, Off

Note: RMT = Reduced and Modified Training, SE = Strength-Endurance, BS = Basic-Strength, T = Transmutation, R = Realization, VL = very light (65-70%), L = light (70-75%), ML = medium light (75-80%), M = medium (80-85%), MH = medium heavy (80-85%), H = heavy (85-95%), VH = very heavy (95-100%). Intensities are based off a set-rep best system (DeWeese, Sams, & Serrano, 2014). Sets and reps in parentheses represent a drop set at approximately 60%. Relative intensities are best on set and repetition best (Carroll et al. 2019a; Stone et al. 1987).

Table 3.2 – Training Programming: Exercise Selection

Strength-Endurance	**Basic-Strength**	**Transmutation**	**Realization**
Monday/Thursday	**Monday/Thursday**	**Monday/Thursday**	**Monday/Thursday**
AM Back Squat **PM** Push Press Jerky Recovery FN Press	**AM** Back Squat **PM** Push Jerk BN Press DB Press	**AM** Back Squat **PM** Jerk Concentric-Only FS BN Press DB Press	**AM** Back Squat* **PM** Jerk BN Press DB Press*
Wednesday	**Wednesday**	**Wednesday**	**Wednesday**
AM Snatch Tech CGSS CG Pull – Floor **PM** Snatch Tech CGSS CG Pull – Knee CG SLDL DB Bent Over Row	**AM** Snatch tech CGSS CG Pull – Floor **PM** Snatch Tech CGSS CG Pull – Knee CG SLDL CG Bent Over Row	**AM** Snatch CGSS CG Pull – PP **PM** Snatch SGSS SG Pull – Knee CG SLDL CG Bent Over Row	**AM** Snatch Tech CGSS CG Pull – Floor **PM** Snatch Tech SGSS SG Pull – PP CG SLDL Inverted Row
Saturday	**Saturday**	**Saturday**	**Saturday**
Snatch Tech	Snatch Tech	SGSS	SGSS

SGSS Snatch SG SLDL DB Bent Over Row	SGSS Snatch C&J SG SLDL SG Bent Over Row	Snatch C&J SG SLDL SG Bent Over Row	Snatch C&J SG SLDL Inverted Row

Note: DB = dumbbell, CG = clean grip, CGSS = clean grip shoulder shrug, SLDL = stiff legged deadlift, SG = snatch grip, SGSS = snatch grip shoulder shrug, FN = front neck, BN = behind the neck, C&J = clean and jerk. *Dropped during last week of taper.

Testing Procedures

Anthropometrics and Hydration

During the initial pre-injury assessment (T0), the athlete's standing height was measured to the nearest 0.01 meters using a stadiometer (Cardinal Scale Manufacturing Co., Webb City, MO), and body mass measured using a digital scale (Tanita B.F. 350, Tanita Corp. of America, Inc., Arlington Heights, IL). The sum of 7 skinfolds (chest, axilla, triceps, subscapular, abdominal, suprailium, thigh) was measured by an International Standards for Anthropometric Assessment (ISAK) certified anthropometrist using a skinfold caliper (Lange, Beta Technology Inc., Cambridge, MD) (3). All measurements were completed at the same time of day by the same experienced technician. Percent body fat and fat free mass were calculated from the sum of skinfolds to assess body composition (29). The athlete's hydration state was estimated using a portable refractometer that calculates urine specific gravity using a scale ranging from 1.000 to 1.060 (Atago 4410 PAL-10S, Tokyo, Japan). If the urine specific gravity ≥1.020, the athlete was instructed to drink water and hydration status was retested after 20 minutes. This continued until the athlete demonstrated adequate hydration.

Ultrasonography

A 7.5 MHz ultrasound probe was used to collect the muscle CSA of the right vastus lateralis (LOGIQ P6, General Electric Healthcare, Wauwatosa, W). The athlete stood upright and placed his weight on his left leg, which was positioned on a 5 cm tall platform, unweighting the right leg, and creating an internal knee angle of 160° ± 10°. The sampling location of the vastus lateralis was at 50% of the distance between the greater trochanter and the lateral epicondyle of the femur. A permanent marker was used to mark the location and the ultrasound probe was covered with water-soluble transmission gel to aid acoustic coupling while avoiding depression of the skin during the scan. The muscle CSA was measured by tracing the inter-muscular image output. All measurements were conducted by the same rater which has been shown to be highly reliable in our laboratory (intra-class correlation coefficient [ICC]: 0.91) (50).

Warm-Up

After ultrasound, a standardized warm-up was administered consisting of 25 jumping jacks which was followed by one set of five dynamic mid-thigh pulls at 20kg, followed by three sets of five dynamic mid-thigh pulls with 60kg. At least one minute of rest was provided between dynamic pulls before beginning jump trials (6,13).

Jumping Performance

Static jumps (SJ) were performed on dual force plates affixed side by side with a sampling frequency of 1000 Hz (Rice Lake Weighing Systems, Rice Lake, WI). The athlete held a near weightless poly-vinyl chloride pipe (0kg, SJ0) and loaded barbell (11kg, SJ11; 20kg SJ20) across their shoulders for unloaded and loaded conditions, respectively. The tester instructed the athlete to squat to a 90° knee angle (i.e., ready position), measured using a handheld goniometer, and instructed to perform a 50% effort warm-up SJ. After a brief rest, the athlete performed another warmup jump at 75% effort. For the trials, the athlete was instructed to assume the ready position and to hold the position until the force-time trace was stable. Once stable, the tester shouted "3, 2, 1, jump!" and the athlete performed a maximal effort jump. The athlete performed at least two maximal jumps at each loading condition. If the difference in jump height (JH) between trials was >2cm, additional trials were performed. This was followed by completion of the countermovement jump (CMJ) using the unloaded (CMJ0) and loaded (CMJ11, CMJ20) protocol. Custom LabVIEW (LabVIEW 2018, National Instruments Co., Austin, TX) programs were used to collect and analyze all data during and post-testing sessions. Performance variables of interest included JH, net impulse (NI), and peak power allometrically scaled (PPa) due to having existing empirical evidence as strong indicators of weightlifting performance (12,41,45–47).

Isometric Mid-Thigh Pull

After completing the jump testing protocol, the athlete performed the IMTP testing on dual force plates (Rice Lake Weighing Systems, Rice Lake, WI). The athlete assumed a mid-thigh pull position, with an approximate knee angle of 125-135º, which was confirmed using a handheld goniometer. The lifter was instructed to perform a 50% effort warm-up isometric pull. After a brief rest, the athlete performed another warmup pull at 75% and was then secured to the bar with both lifting straps and athletic tape (41). The athlete was instructed to "pull as fast and hard as possible" beforehand. For the trials, verbal instruction was given to get into position and apply a steady amount of pre-tension to the bar to reduce slack in the body, and to help minimize a countermovement. Once a consistent force trace was observed by the tester a verbal countdown of "3, 2,1, pull!" was given until the tester noticed a plateau or decrease in force. Athletes then received 90-120 seconds of seated rest before reattempting. Additional trials were performed if there was a >250N difference in peak force from the first attempt. The force trace was analyzed by the same investigator using custom designed lab view software (National Instruments, Austin, TX) (6,13). Variables of interest for IMTP included isometric peak force (IPF), IPF allometrically scaled (IPFa), rate of force development (RFD) at 200 ms (RFD200) and 250 ms (RFD250). These variables were selected per their well-documented relationships with weightlifting performance (6,19,25,42).

Statistical Analyses

Tau-U was calculated using an online calculator (http://singlecaseresearch.org/calculators/tau-u). Tau-U is an effect size used in single-case research that combines nonoverlap between phases (36,37,39). It also provides an option to control monotonic trend, which is the tendency for scores to increase over time (undesirable baseline trend) (36,37). For this analysis, all calculations were corrected for baseline. A hypothetical series (A) of data was set up, which represented a situation in which the athlete never returned to the pre-injury level of performance and compared changes pre-injury (T0) to post-injury (T0-T4). Alpha level for all analyses was set at $p \leq 0.05$. All other analyses were performed using Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA).

RESULTS

Isometric Mid-Thigh Pull

There was a statistically significant increase between the hypothetical series A and an actual series representing T0-T4 for RFD250 (*p*=0.0367; Tau-U=0.8; Figure 3.2), IPF (*p*=0.0367; Tau-U=0.8; Figure 3), and IPFa (*p*=0.0367; Tau-U=0.8; Figure 4). No other IMTP variables reached statistical significance.

Table 3.3 - IMTP & US

	T0	T1	T2	T3	T4
IMTP					
RFD200 ($N*s^{-1}$)	16956.1±14.7	15969.5±1216.4	20744.2±1156.9	18000.7±4214.7	18624.4±3274.9
RFD250 ($N*s^{-1}$)	14389.6±6.8	16214.9±1045.4	17593.3±1016.4	17142.4±3283.5	16622.2±2396.9
IPF (N)	8558.9±22.2	10043.6±97.4	10892.2±274.5	10750.9±219.3	10636.6±272.3
IPFa ($N*kg^{-0.67}$)	330.3±0.9	369.87±3.6	398.31±10.0	392.78±8.0	386.81±9.9
Ultrasound					
CSA (cm^2)	49.7±1.2	52.02±0.5	53.9±0.1	52.1±0.13	52.6±1.2

Notes: RFD-rate of force development, IPF-isometric peak force, IPFa-isometric peak force allometrically scaled for body mass, CSA-muscle cross sectional area

Table 3.4 - IMTP & US Percent Change

	T0 vs T1	T0 vs T2	T0 vs T3	T0 vs T4	T1 vs T2	T1 vs T3	T1 vs T4
IMTP							
RFD200 ($N*S^{-1}$)	-5.82%	22.34%	6.16%	9.84%	29.90%	12.72%	16.62%
RFD250 ($N*S^{-1}$)	12.69%	22.26%	19.13%	15.52%	8.49%	5.71%	2.51%
IPF (N)	17.35%	27.27%	25.61%	24.28%	8.45%	7.04%	5.90%
IPFa ($N*kg^{-0.67}$)	11.98%	20.59%	18.92%	17.11%	7.69%	6.19%	4.58%
Ultrasound							
CSA (cm^2)	4.63%	8.32%	4.69%	5.82%	3.53%	0.06%	1.14%

Notes: T0 vs other time points represent comparisons between pre-and-post injury. T1 vs other time points compare how each value changed over the course of the stage. RFD-rate of force development, IPF-isometric peak force, IPFa-isometric peak force allometrically scaled for body mass, CSA-muscle cross sectional area

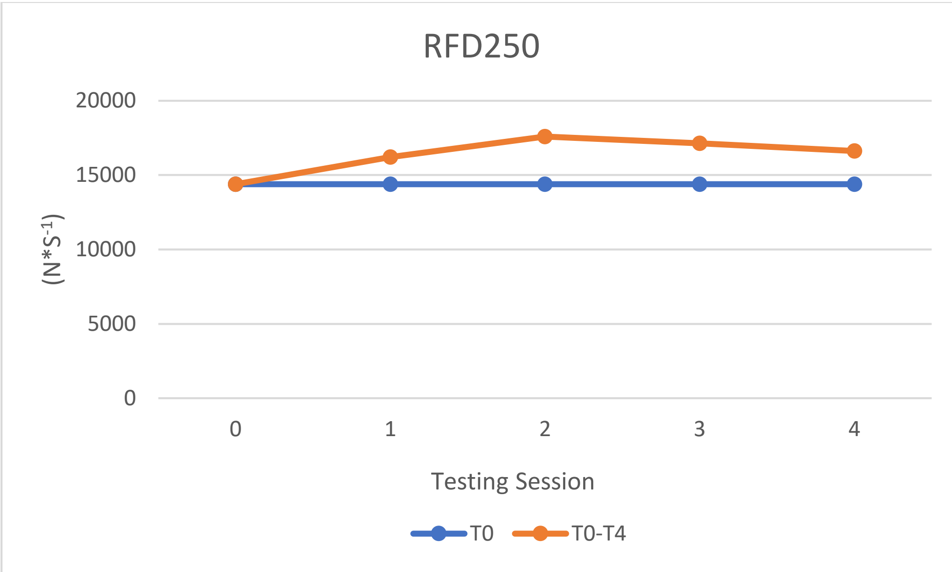

Figure 3.2. RFD250. T0-Week 0, T1-Week 12, T2-Week 15, T3-Week 18, T4-Week 22

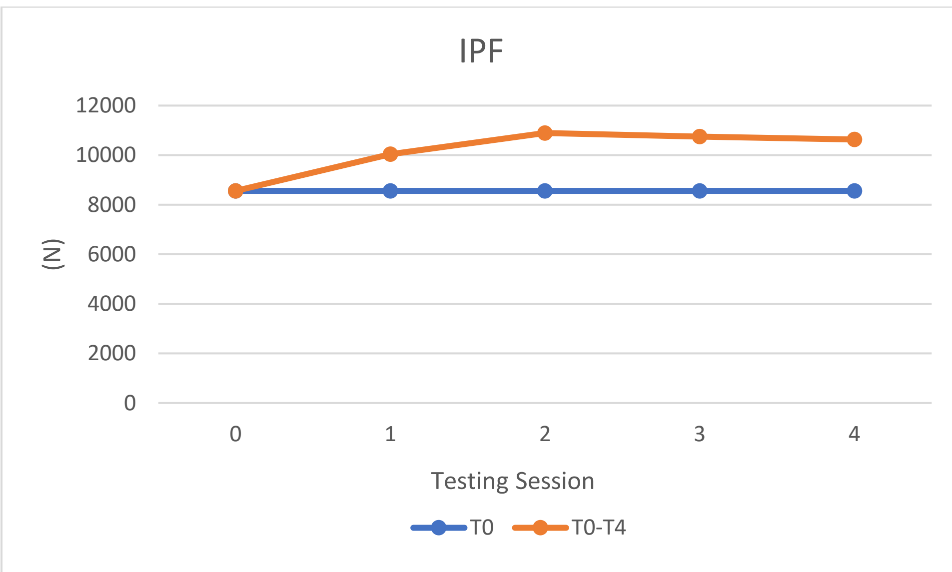

Figure 3.3. IPF. T0-Week 0, T1-Week 12, T2-Week 15, T3-Week 18, T4-Week 22

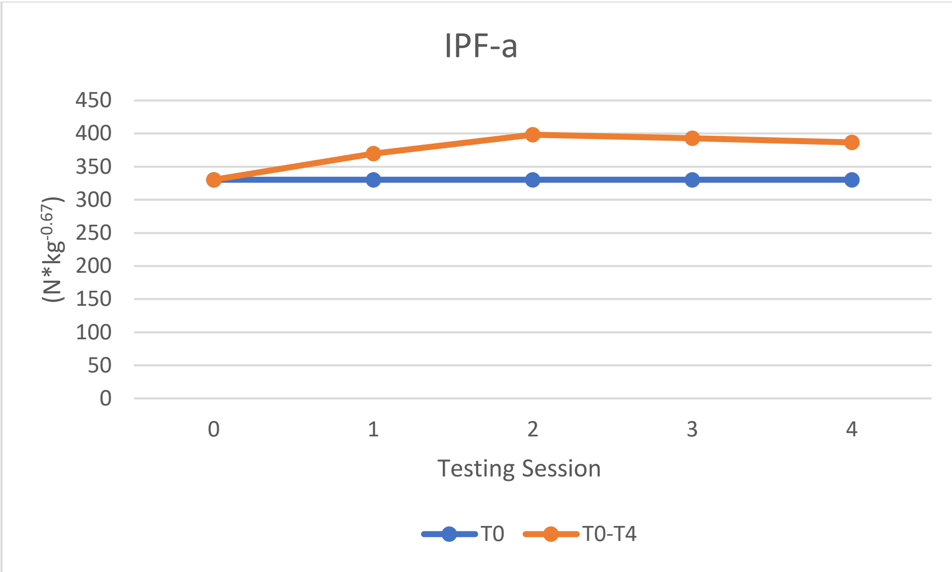

Figure 3.4. IPF-a. T0-Week 0, T1-Week 12, T2-Week 15, T3-Week 18, T4-Week 22

Muscle CSA and Skinfold

An increase in muscle CSA was found between T0-T4 and T0 (p=0.0367; Tau-U=0.8; Figure 6). Body fat percentage increased from 23.6% to 24.6% from T0-T1 and increased up to 26.17% at T4. Concurrently, FFM increased from 101.69kg to 106.76kg from T0-T1 and increased further to 106.98kg at T4.

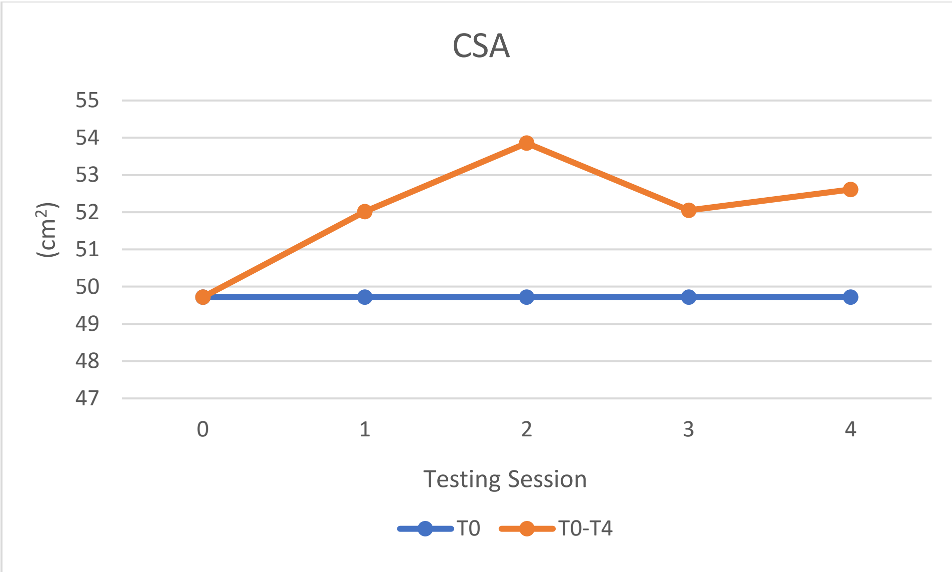

Figure 3.5. Muscle CSA. T0-Week 0, T1-Week 12, T2-Week 15, T3-Week 18, T4-Week 22

Jump Performance

No statistically significant differences were found in any of the jump variables across all SJ and CMJ unloaded and loaded conditions. However, jump performance did appear to return to pre-injury baseline values.

Table 3.5 – Pre- to Post-Study Jump Performance

Variable	**T0**	**T1**	**T4**
SJ			
SJH 0kg (cm)	34.9±1.6	29.4±3.5	39.3±0.1
SJNI 0kg (N*s)	356.4±8.0	341.8±20.0	395.2±1.1
SJPPa 0kg ($W*kg^{-0.67}$)	59.9±0.1	48.2±3.5	57.5±0.6
SJH 11kg (cm)	30.2±0.8	28.7±0.1	32.9±5.5
SJNI 11kg (N*s)	355.4±4.3	362.8±0.7	387.9±21.1
SJPPa 11kg ($W*kg^{-0.67}$)	54.9±1.6	49.6±0.9	52.2±2.8
SJH 20kg (cm)	27.9±0.4	26.2±0.6	27.6±1.8
SJNI 20kg (N*s)	362.0±2.4	370.9±2.2	383.4±8.2
SJPPa 20kg ($W*kg^{-0.67}$)	53.9±0.5	49.4±0.2	50.4±1.6
CMJ			
CMJH 0kg (cm)	36.8±0.4	35.1±1.3	35.0±0.5

CMJNI 0kg (N*s)	364.6±1.5	373.3±7.3	381.5±0.7
CMJPPa 0kg (W*kg$^{-0.67}$)	62.3±0.2	54.6±2.5	55.6±2.3
CMJH 11kg (cm)	32.9±0.8	30.6±1.3	29.1±1.8
CMJNI 11kg (N*s)	368.7±3.4	373.4±7.0	383.7±5.9
CMJPPa 11kg (W*kg$^{-0.67}$)	59.4±0.9	51.3±1.0	51.4±2.4
CMJH 20kg (cm)	31.0±1.2	28.8±0.6	30.7±3.2
CMJNI 20kg (N*s)	380.5±6.0	387.8±2.9	404.6±17.9
CMJPPa 20kg (W*kg$^{-0.67}$)	57.5±0.1	52.5±0.5	52.5±3.5

Notes: SD-standard deviation, SJ-static jump, CMJ-countermovement jump, JH- jump height, NI-net impulse, PPa-peak power allometrically scaled for body mass

Table 3.6 – Jump Performance Percent Change

	T0 vs T1	**T0 vs T4**	**T1 vs T4**
SJ			
SJH 0kg (cm)	-15.64%	12.77%	33.67%
SJNI 0kg (N*s)	-4.09%	10.89%	15.62%
SJPPa 0kg (W*kg$^{-0.67}$)	-19.53%	-4.13%	19.15%
SJH 11kg (cm)	-5.13%	8.94%	14.83%
SJNI 11kg (N*s)	2.08%	9.12%	6.90%
SJPPa 11kg (W*kg$^{-0.67}$)	-9.81%	-4.99%	5.35%
SJH 20kg (cm)	-6.09%	-1.08%	5.34%
SJNI 20kg (N*s)	2.47%	5.91%	3.36%
SJPPa 20kg (W*kg$^{-0.67}$)	-8.26%	-6.38%	2.05%
CMJ			
CMJH 0kg (cm)	-4.76%	-5.03%	-0.29%
CMJNI 0kg (N*s)	2.36%	4.63%	2.21%
CMJPPa 0kg (W*kg$^{-0.67}$)	-12.37%	-10.87%	1.71%
CMJH 11kg (cm)	-7.00%	-11.42%	-4.75%
CMJNI 11kg (N*s)	1.27%	4.08%	2.77%
CMJPPa 11kg (W*kg$^{-0.67}$)	-13.68%	-13.48%	0.23%
CMJH 20kg (cm)	-7.11%	-0.97%	6.61%
CMJNI 20kg (N*s)	1.92%	6.34%	4.34%
CMJPPa 20kg (W*kg$^{-0.67}$)	-8.75%	-8.71%	0.05%

Notes: T0 vs other time points represent comparisons between pre-and-post injury. T1 vs other time points compare how each value changed over the course of the stage. SD-standard deviation, SJ-static jump, CMJ-countermovement jump, JH-jump height, NI-net impulse, PPa-peak power allometrically scaled for body mass

Competition Performance and Body Mass

At COMP1, the subject weighed 131.9kg and lifted 122kg in the Snatch and 160kg in the Clean and Jerk, totaling 282kg with a Sinclair score of 289.62. After injury, the subject weighed 141.5kg at T1, 143kg at T2, 143.2kg at T3, 143.6kg at COMP2, and 144.2kg at T4. At COMP2 (~5.5 months post-surgery), the subject lifted 126kg in the Snatch, 165kg in the Clean and Jerk, totaled 291kg, and had a Sinclair score of 294.85. As an outside assessment post-observation, the athlete continued to improve performance in competition. At COMP3 (~9 months post-surgery), the subject weighed 149.26kg, lifted 125kg in the Snatch, 170kg in the Clean and Jerk, totaled 295kg, and had a Sinclair score of 297.539. At COMP4 (~16 months post-surgery), the subject weighed 147.50kg, lifted 128kg in the Snatch, and 175kg in the Clean and Jerk, totaling 303kg with a Sinclair score of 306.006. At COMP5 (~21.75 months post-surgery), the subject weighed 145.5kg, lifted 133kg in the Snatch, 180kg in the Clean and Jerk, totaled 313kg, and had a Sinclair score of 316.615. At COMP6 (~25.75 months post-surgery), the subject weighed 151.4kg and lifted 134kg in the Snatch, 180kg in the Clean and Jerk, totaled 314kg, and had a Sinclair score of 316.247. At COMP7 (~30.75 months post-surgery), the subject weighed 152.11kg, lifted 131kg in the Snatch, 176 kg in the Clean and Jerk, totaled 307kg, and had a Sinclair score of 309.059. Finally, at COMP8 (~33.75 months post-surgery), the subject weighed 154.2kg, lifted 137kg in the Snatch, 182kg in the Clean and Jerk, totaled 319kg, and had a Sinclair score of 320.750.

DISCUSSION

The purpose of this observation was to 1) retrospectively investigate the efficacy of a modified block periodization protocol designed for rehabilitation purposes, 2) determine the practicality of sport specific athlete monitoring tools with selected variables that best explain weightlifting based training adaptations, and 3) assess pre- to post-injury performance changes in a collegiate male weightlifter following a right knee meniscal injury. The primary findings of this investigation were that a) the use of block periodization and the implementation of phase potentiation style programming (43) successfully rehabilitated the athlete resulting in b) muscle size being maintained and improved, which c) may have further contributed to observed laboratory- and competition-based performance improvements.

The most notable finding within this observation is that the athlete was able to improve competition performance on the platform at COMP2 compared to COMP1. The current observation suggests that block periodization was an effective means of rehabilitation for this weightlifter. However, improvements in technical proficiency in the lifts through the use of block periodization and appropriate programming could have contributed to improvements in performance, though this was not directly investigated. It is also possible that with the lifter increasing body mass during this reduced training period, this aided with injury recovery and his return to the platform.

As noted, the athlete experienced substantial increases in body mass (9.3%Δ and 11.3kg from T0-T4), body fat (11%Δ and 2.6% from T0-T4), and FFM (5.2%Δ and 5.3kg from T0-T4) over the course of the study. These findings are likely attributable to a positive energy balance and an increase in net protein balance (26,35) during the reduced training. However, this is only a speculative assumption as nutrition and macronutrient intake was not accounted for. It is also likely that the many of observed performance improvements are a direct by-product of the increases in body size as well as improvements in strength and explosive strength production. Furthermore, the large increases in body size could also explain the muscle CSA increases observed over the 13-week period.

It has been shown that increases in muscle CSA are advantageous for weightlifting performance (17). Increased muscle size has been shown to produce strong relationships with muscle strength capabilities (32,34). There is also an array of data suggesting that muscle CSA can be indicative of jumping performance, isometric strength, squat strength, and weightlifting performance (5,10,28,40,44,52). Further, data suggest that muscle CSA is closely related to later RFD time bands (≥150ms) (16) although this information is limited. The gains in muscle CSA, as a by-product of body mass increases, were likely associated with the observed improvement for IPF, IPFa, and RFD250 (p=0.0367). Thus, our data agrees with the relationships reported in the current literature. This output is also assumed based on the statistically significant relationship between IPF and RFD250 ($r = 0.729$, $p < 0.05$) (6,7), though exact relationships may differ between athletes. Nevertheless, jumping performance has been more consistent with determining weightlifters' recovery, adaptation, and competition-based changes which warrants further discussion.

Multiple studies have previously reported strong relationships between jump capabilities and competition-based weightlifting performance (12,18,46,49). However, SJ has been shown to have a stronger relationship to weightlifting performance than CMJ (21,46), likely due to its biomechanical similarity to the initial starting position of weightlifting movements. While JH measured by flight time is easy to collect and most prominent in the literature, it can be substantially affected by changes in body mass (45). However, small decreases or a maintenance in JH should not be interpreted as a lack of positive adaptation for a weightlifter (8,45), especially when the athlete maintains performance despite increases in body mass. This is particularly important when applied to the monitoring of any athletes whose sport or position relies more on generating a large NI and displacing another object, compared to the ability to displace themselves, as is the case for weightlifters. The NI associated with these jumps showed increases that were likely reflected in weightlifting performance, with improvements in the snatch (122kg to 126kg), clean and jerk (160kg to 165kg), total (282kg to 291kg), and Sinclair score (289.62 to 294.85). This observation has been corroborated by a recent paper out of our lab (45) indicating a generalizable relationship existing between Sinclair with JH and NI within-individual athletes. The increases in NI or JH could also be considered indicators of greater Sinclair score potential within individual lifters. Thus, the athlete's inability to improve jumping performance overall is likely reflective of his inability to proportionately displace a greater mass.

Given most variables in this study did not reach statistical significance when compared to pre-injury, this may be indicative of the fact that over the course of the retraining period, nearly all performance variables returned to or slightly improved from baseline in both absolute and percent terms. Most importantly, these adaptations appear to have allowed further improvement in the snatch, clean and jerk, weightlifting total, and Sinclair score. This case study is a demonstration of the efficacy of using short-term block periodized models of training in athletes returning from a right knee meniscal tear, in as few as 21 weeks of training. However, this study is not without limitations. An important limitation in this study was that testing took place three days after the day of competition which likely inflated laboratory-based performance metrics via complete rest (i.e., RFD values). Thus, differences in travel logistics and competition results between timepoints could have also influenced these results. Indeed, it is possible that very positive or negative competition outcomes may have influenced the athletes' mental state and motivation to perform during the testing sessions. Therefore, it is possible that the relationships between the testing performances and competition observed within this investigation could have been influenced by a previous successful performance resulting in greater motivation during the proceeding testing sessions. Additionally, the findings of this study are limited due to a single athlete, the specific injury that occurred (right knee meniscus), and the weight/weight class of the athlete (109kg+, super-heavyweight).

PRACTICAL APPLICATION

During injuries, coaches can still train athletes but should monitor the athlete day-to-day while incorporating reduced and modified training under a block periodization programming framework. Sports scientists and coaches should also implement athlete monitoring tools that provide appropriate feedback relative to the individual and sport. Additionally, the use of electronic dietary logs such as MyFitnessPal, MyPlate, Cronometer, and others should be considered to monitor water intake, macronutrient and micronutrient intake, and body mass changes. This should help combat nutritional inadequacies that can cause issues with recovery and, therefore, increased injury risk. Lastly, sports scientists and coaches may benefit from monitoring body mass changes during injury, as excessive weight gain, in combination with reduced volume and intensity, may lead to disproportionate gains in fat mass, which is not beneficial for weight-class sports.

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Chapter 4. Summary and Future Investigations

The purpose of this observation was to 1) retrospectively investigate the efficacy of a modified block periodization protocol designed for rehabilitation purposes, 2) determine the practicality of sport specific athlete monitoring tools with selected variables that best explain weightlifting based training adaptations, and 3) assess pre- to post-injury performance changes in a collegiate male weightlifter following a right knee meniscal injury. The primary findings of this investigation were that a) the use of block periodization per the implementation of phase potentiation style programming successfully rehabilitated the athlete, which resulted in b) muscle size being maintained, that c) may have further contributed to observed laboratory- and competition-based performance improvements for a super-heavy weight class weightlifter returning from a right knee meniscal injury.

Although infrequent, injuries still occur in weightlifting, with the knee being the most common site of injury (Aasa et al., 2017; Keogh & Winwood, 2016). This is the first study to demonstrate the efficacy of using a modified block periodization protocol for rehabilitation of a weightlifter with this injury. However, it is likely that the combination of training stimulus with significant increases in body mass obviated performance decrements and contributed to the increases in muscle CSA, IPF, IPFa, and RFD250 found in this study. Nevertheless, it shows the importance of adequate calorie and protein consumption during injury to facilitate recovery and return to the platform.

While significant increases in jump performance may not have been realized, an increase in NI was observed, lending credence to recent arguments from Bishop et al. (2021) and recent findings out of our lab (Suarez et al., 2022). This line of thinking is particularly important when applied to the monitoring of any athletes whose sport or position relies more on generating a large NI and displacing another object, compared to the ability to displace themselves, as is the case for weightlifters. Thus, increases in JH or NI might be considered indicators of weightlifting success (Suarez et al., 2022). Implementing appropriate athlete monitoring over the course of an athlete's career will likely aid in optimizing performance while minimizing injury risk.

Future investigations should seek to collect jump data more frequently (e.g., monthly) to examine changes in performance particularly leading up to competition. This should allow stronger inferences to be made as to the relationship between jump performance and competition, as well as the effects of each block on jump performance. Additionally, data collected around competition should be as close to competition day as possible to reduce the potential impact of traveling logistics and mood states impact on performance during testing. Considering modern day technology, future investigations should also implement electronic dietary logs to ensure athletes are eating and drinking properly which could potentially raise concern if macronutrients such as protein or carbohydrate intake is not adequate.

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