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A narrative review of velocity-based training best practice: the importance of contraction intent versus movement speed

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Abstract

Explosive movements requiring high force and power outputs are integral to many sports, posing distinct challenges for the neuromuscular system. Traditional resistance training can improve muscle strength, power, endurance, and range of motion; however, evidence regarding its effects on athletic performance, such as sprint speed, agility, and jump height, remains conflicting. The specificity of resistance training movements, including velocity, contraction type, and joint angles affects performance outcomes, demonstrates advantages when matching training modalities with targeted sports activities. However, independent of movement speed, the intent to contract explosively (ballistic) has also demonstrated high velocity-specific training adaptations. The purpose of this narrative review was to assess the impact of explosive or ballistic contraction intent on velocity-specific training adaptations. Such movement intent may predominantly elicit motor efferent neural adaptations, including motor unit recruitment and rate coding enhancements. Plyometrics, which utilize rapid stretch-shortening cycle movements, may augment high-speed movement efficiency and muscle activation, possibly leading to improved motor control through adaptations like faster eccentric force absorption, reduced amortization periods, and quicker transitions to explosive concentric contractions. An optimal training paradigm for power and performance enhancement might involve a combination of maximal explosive intent training with heavier loads and plyometric exercises with lighter loads at high velocities. This narrative review synthesizes key literature to answer whether contraction intent or movement speed is more critical for athletic performance enhancement, ultimately advocating for an integrative approach to resistance training tailored for sports-specific explosive action.

Key words: resistance training, strength, power, plyometric exercise, speed, stretch-shortening cycle

Introduction

It may be surprising to segments of the younger generation that resistance training (RT) as a tool to improve athletic performance has only been considered as an essential element of training for approximately 50 years in the western world. In the 1960s and prior, football, ice hockey, rugby players, track and field, and other athletes would not indulge in RT as it was thought to create muscle boundness (tense, rigid, inflexible, hypertrophied muscles), which would presumably slow the athlete, adversely affect co-ordination and restrict range of motion (ROM) (Todd 1985). Conversely, athletes from Eastern bloc countries (e.g., Soviet Union, East Germany) took advantage and harnessed the benefits of RT sooner than western athletes. It was not until Eastern bloc athletes were emerging victorious in Olympic competitions, the success of Soviet so-called amateur ice hockey players competing against Canadian professionals (1972 Summit Series), and other competitions, that the west took notice of the advantage of RT.

The traditional RT techniques and methodologies originating in the 1970s primarily followed DeLorme's recommendations of 3 sets of 6–15 repetitions performed at a controlled pace (Delorme 1945; Delorme et al. 1952). The scientific findings and practical realizations over the last 50 years have revealed the muscle boundness theory to be false. Early research involving conventional RT demonstrated improvements in movement (Clarke and Henry 1961; Smith and Whitley 1965) and reflex (Tipton and Karpovich 1966; Francis and Tipton 1969) time. Recent meta-analyses (Afonso et al. 2021; Alizadeh et al. 2023) demonstrated that RT increases ROM to a similar degree as static stretch training, challenging previous misconceptions about the original muscle boundness (rigid, inflexible muscles) theories.

Increases in maximal strength and muscle hypertrophy are often attributed to increased success in a variety of sports that rely on high force output and/or greater body masses (e.g., North American football, ice hockey, rugby, and others). However, there is mixed evidence that slow controlled RT consistently improves all athletic performance variables. Steele et al. (2020) suggested that evidence for the beneficial effect of RT on athletic performance is primarily observational and derived from cross-sectional studies with the evidence often limited and focused on *proxy* measures of sports performance (e.g., maximal voluntary isometric contraction (MVIC) strength, 1 repetition maximum (RM), jump height) in studies using small sample sizes. Early research (1980–90s) reported positive correlations between vertical jump height and leg strength (Hakkinen 1989; Jaric et al. 1989; 1993; Young and Bilby 1993; Ashley and Weiss 1994). It was suggested that maximum strength may be important for squat jumps and countermovement jumps (Young et al. 1995) as the concentric phases of these jumps are relatively long duration (∼300–900 ms) (Bobbert et al. 1987; Hakkinen 1989) and even movements exceeding just 250 ms are highly influenced by maximal strength (Schmidtbleicher 1992). However, Young et al. (1995) reported that maximum strength did not significantly correlate with standing and run-up vertical jump or drop jumps, whereas reactive strength (capability to rapidly change from an eccentric to a concentric muscular contraction) did demonstrate significant correlations especially with the run-up jump. Pedersen et al. (2019) also reported that maximal strength training improved maximal strength in female soccer players to a large magnitude; but with no positive transfer effects on sprint speed or jump height.

Whereas isometric strength training can improve maximal force, the rate of force development (RFD) may not always increase. It is hypothesized that there are specific neural or muscular adaptations underlying RFD changes, independent of improvements in maximal strength (Del Vecchio et al. 2022). Del Vecchio et al. (2022) reported that strength training did not alter RFD since there was no change in motor unit recruitment frequency or their initial discharge rate during rapid contractions. Hence, maximal strength and contraction speed are determined by different motoneuron behavior adaptations with motoneuron recruitment speed increases necessary to evoke training-induced increases in RFD. Earlier, Inglis et al. (2017) reported that maximal voluntary strength (torque) of the tibialis anterior accounted for sex differences in voluntary rate of torque development. However, there were peripheral (muscle) evoked sex differences, with females experiencing longer evoked electromechanical delay but no differences in voluntary electromechanical delay. They also suggested that over just three testing days, a greater rate of increase in electromyography (EMG) with a significant reduction in electromechanical delay may reveal that females might incorporate a different motor unit activity pattern than males at contraction onset. Therefore, while traditional RT demonstrated debatable benefits to overall athletic performance, another concept was developed that portended to provide better transfer effects to athletic performance: "velocity specificity".

Training specificity

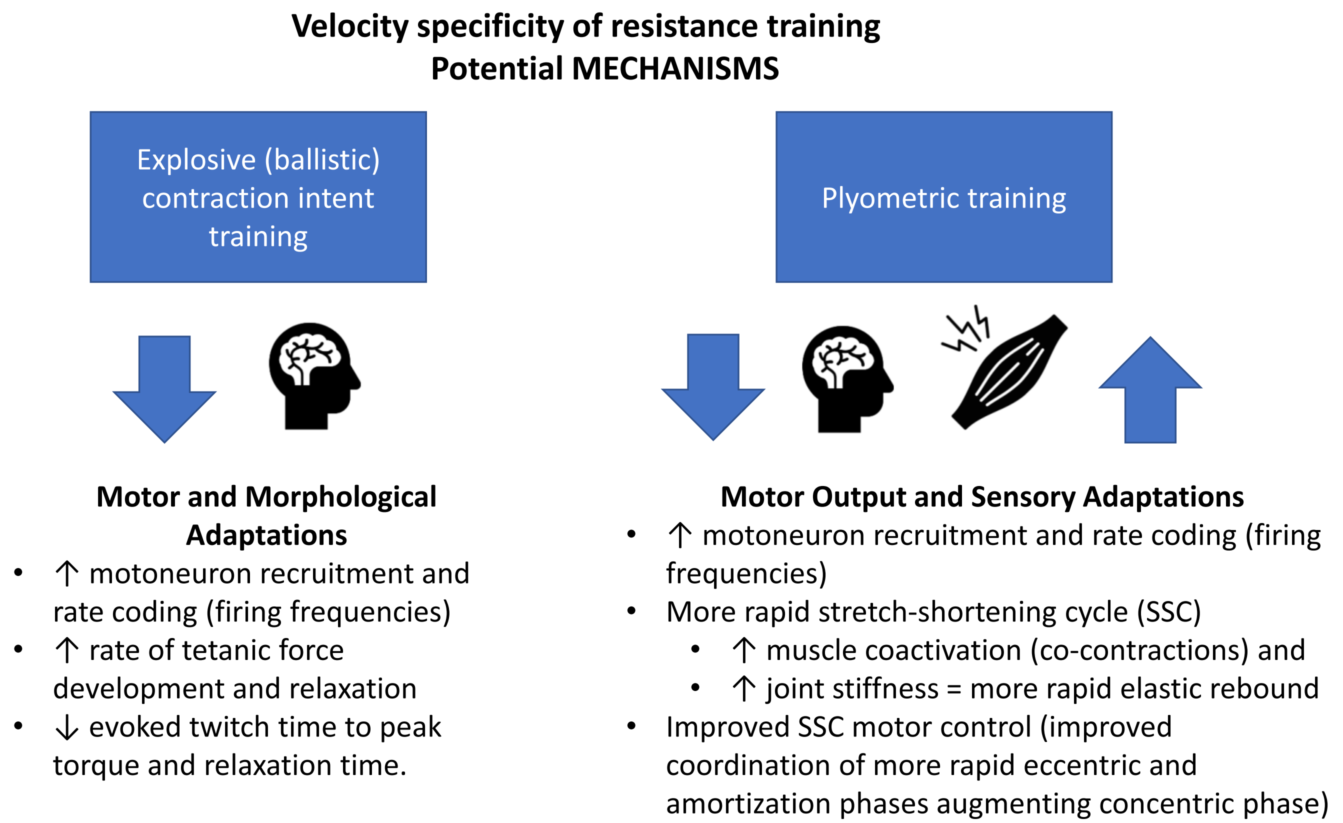
The concept of movement or training specificity in RT refers to more pronounced improvements in strength or power when the training more closely matches the movement patterns, contraction types, angles, ROM, and velocity relevant to the athlete's sport (Rasch and Morehouse 1957; Sale and MacDougall 1981; Behm and Sale 1993*b*). Velocity specificity of RT infers that the greatest strength and power increases occur when the training velocity closely matches the task (Knapik and Ramos 1980; Behm and Sale 1993*b*). While not all early research reported velocity specific effects (Behm 1991), most of the nascent research in this area consistently emphasized the importance of matching the movement training and task velocity (Moffroid and Whipple 1970; Lesmes et al. 1978; Caiozzo et al. 1981; Kanehisa and Miyashita 1983*a*, 1983*b*; Hakkinen et al. 1985*a*, 1985*b*; Hakkinen and Komi 1986).

RT programs emphasizing speed strength have shown significant enhancement of vertical jump performance (Hakkinen and Komi 1985; Brown et al. 1986; Adams et al. 1992; Wilson et al. 1993; Wilson and Murphy 1995; Holocomb et al. 1996). Given, power = force *x* velocity, it stands to reason that traditional strength or RT programs (increased force outputs) would contribute to improved power, but programs that involve both force and velocity (i.e., speed strength, plyometrics) should induce training adaptations in both variables contributing to even greater efficacy.

However, a unique piece of research challenged the concept of the necessity for high movement velocity by emphasizing muscle contraction velocity and the intent to contract explosively or ballistically (high rate of force development) (Behm and Sale 1993*a*). Behm and Sale trained 16 university students for 16 weeks with one limb (dorsiflexors) trained isometrically (no movement velocity) and the contralateral dorsiflexors trained at 300 ^{0}/s. According to the velocity specificity concept, the 300 ^{0}/s trained limb should have shown the greatest strength gains at higher testing velocities. However, for each contraction whether it was isometric or higher isokinetic velocity, the participants were told to contract explosively or ballistically (intent to contract as hard and as fast as possible). Following training, the outcomes revealed that both groups, irrespective of training modality achieved greater force outputs at higher testing velocities indicating that the type of muscle movement/action (no velocity isometric vs. higher velocity isokinetic) was not a significant factor and it was the ballistic, explosive, contraction intent that induced the high velocity specific adaptations.

Based on the initial Behm and Sale (1993*a*) ballistic-intent publication, this review endeavoured to provide a narrative review on the findings of ballistic (explosive)-intent contraction research over the last 31 years on physical performance. Secondly, an attempt is made to integrate adaptations associated with ballistic-intent RT with high velocity plyometric training to highlight the practical training mechanisms, implications, and recommendations.

Fig. 1. Velocity specificity of resistance training (RT): potential mechanisms. Explosive (ballistic) intent versus plyometric training.



Search strategy

To identify all relevant studies, a literature search was completed by January 2024 using PubMed (814 articles), Scopus (1380 articles), Sports Discus (692), and Web of Science (443). Using AND and OR Boolean operators, a systematic search was conducted using the following keywords: (((((((("maximal intent") OR ("velocity specificity")) OR ("velocity specific")) OR ("maximal intended")) OR ("explosive intent")) OR ("intention to squat explosively")) OR ("velocity-based")) OR ("explosive strength training")). The search garnered 3208 articles of which there were 1131 duplicates, and 97 were non-English language articles. Exclusion criteria included less than 2 weeks of RT, unhealthy participants, a lack of a control group, and non-English language articles. The systematic search was conducted by three independent researchers (SA, SHA, RC). Initially, the articles were screened by their title and then abstract. If the content remained unclear, the full text was retrieved for further screening and identifying the relevant papers. Following this independent screening process, the researchers compared their findings. Disagreements were resolved by jointly reassessing the studies against the eligibility criteria. Moreover, review papers, case reports, special communications, letters to the editor, invited commentaries, conference papers, or theses were excluded. The final tally of strictly applicable ballistic-, explosive-, or maximal velocity-intent publications was 25 articles.

High velocity or ballistic-intent training

Subsequent to the Behm and Sale (1993*a*) ballistic-intent article, other studies also reported beneficial training gains with similar high velocity intent training routines. Balshaw et al. (2016) compared 12 weeks of thrice weekly (40 knee extension repetitions) explosive-contractions (1 s), versus sustained-contractions RT (gradual increase to 75% of maximum voluntary torque and then sustain for 3 s). They found greater increase with sustained contraction for MVIC torque (23% vs. 17%; effect size (ES): 0.69), and quadriceps hypertrophy (8.%1 vs. 2.6%; ES: 0.74) with similar neural drive enhancements, whereas explosive contractions significantly improved explosive torque at all time points (0–50, 0–100, 0–150 ms by 17%–34%; ES: 0.54–0.76). Sustained contractions increased explosive torque only at 150 ms (12%; ES: 1.48). Moreover, Gonzalez-Badillo et al.'s (2014) RT program intervention of 3 times per week for 6 weeks with maximal intended velocity contractions against maximal or half maximal concentric velocity bench press movements demonstrated significantly higher 1RM improvements and velocity produced against light and heavy loads with the maximal velocity training suggesting that maximal intent training is more effective when implemented with maximal velocity movements.

Behm and Sale (1993*b*) in their review rationalized that the explosive contraction intent training primarily induced neural adaptations such as increased motoneuron rate coding (firing frequencies) (Fig. 1). Similar mechanisms were reported with an EMG nonlinear scaled wavelet analysis of high speed isoinertial RT, which demonstrated increased wavelet intensity with increased movement speed suggesting increased motor unit synchronization, earlier and more substantial recruitment of larger, fast contracting motor units, increased rate coding, and the emergence of doublets (Napoli et al. 2015).

However, the possibility for peripheral muscle adaptations have also been reported. The Behm and Sale (1993*a*) explosive-intent article found not only voluntary force adaptations but also peripheral evoked muscle adaptations with increased rate of tetanic force development (47%) and relaxation (26%) as well as decreases in evoked twitch time to peak torque (6%) and relaxation time (11%). Furthermore, Maffiuletti and Martin (2001) corroborated these finding with their recruitment of 16 young, healthy male adults to perform knee extension MVIC training (six sets of six repetitions) thrice weekly for 7 weeks with either progressive 4 s MVICs or ballistic-intent 1 s MVICs. Knee extensors concentric, eccentric, and isometric voluntary torque significantly increased for both training groups. Quadriceps evoked stimulation, increased the amplitude and duration of the muscle action potential (M-wave) with the progressive MVIC group whereas ballistic-intent contractions altered evoked twitch contractile properties (increased peak twitch torque, contraction time, and maximal rate of twitch relaxation and decrease of the half relaxation time). Hence, these studies provided compelling evidence of training-specific muscular adaptations to the rate of contraction training with ballistic-intent training affecting the contractile muscle properties (i.e., excitation-contraction coupling).

However, the literature is not unanimously positive as not all studies consistently report velocity-specific responses. Eight weeks of dynamic (elastic resistance bands), or isometric (unyielding strap) punch training had both groups intentionally contracting explosively into the punch (Dinn and Behm 2007). Whereas EMG activity increased in both groups, MVIC force did not improve, but movement time improved to a greater extent in the dynamic training group. Hence in this study, the movement velocity provided a greater benefit than isometric ballistic-intent for improving punching speed (Dinn and Behm 2007). Perhaps the dynamic, multi-articular action of punching necessitated greater movement control and motor learning, which was not facilitated with the isometric maximal intent contractions (punches). A 10-week training program with female netball players involving a strength-trained (80% 1RM at an average training velocity $= 0.308$ m.s^{-1}), power-trained (60% 1RM—average training velocity $= 0.398$ m.s^{-1}) and a control group revealed that the strength-trained individuals had significantly greater increases in mean volume of weight lifted and power output compared to the power and control groups (Cronin et al. 2001). There was a lack of functional velocity specificity as the strength-trained and power-trained groups similarly improved netball throw velocity. The limitation of this study was the disparity between training velocity and actual netball throwing velocity (11.38 m.s^{-1}). This limitation is common in the literature where there is often an incongruence between typical training velocities associated with isoinertial and isokinetic training compared to many sport activities. For example, the knee angular velocity of elite sprinters can achieve a mean of 1185 ^{0}/s (minimum to maximum: 874–1397 ^{0}/s) (Miyashiro et al. 2019), whereas typical isokinetic training devices have a maximum angular velocity of 300–450 ^{0}/s. Pearson et al. (2024) trained 20 untrained, 30–60-year old participants for 6 weeks either with maximal contraction velocity intent or controlled tempo and found significant improvements in all anthropometric and functional measures (i.e., body mass, body mass index, strength-to-mass ratio, bipedal balance, 6 min walk test, 30 s sit-to-stand, timed up and go, and leg press 1RM) but no significant advantage for either intervention. A possible explanation is that with untrained individuals there is a generalized, non-specific, positive training response to all types of training interventions.

However, a meta-analysis by Pearson et al. (2022) of 12 studies examining functional capacity in older adults with maximal intent training demonstrated significantly greater improvements for timed-up-and-go and knee extension 1RM with maximal intent versus traditional strength training, whereas traditional strength training found more favourable results with the 30 s sit-to-stand test. With all functional capacity outcomes combined, there was no statistically significant difference between training methods, but near-significance greater benefits with maximal intent training for strength-related outcomes (Pearson et al. 2022). Hence, there is some evidence that the intent to contract explosively or rapidly may promote corticospinal adaptations concerning recruitment, rate coding, and other neural responses that lead to high velocity-specific strength/power gains. However, these ballistic-intent training adaptations may not be as evident in movement involving multi-articular coordination.

Plyometrics

These ballistic or explosive contraction intent findings do not suggest that explosive intent and slow movement are the only or most effective training routine. Cronin et al. (2001) suggested that the repeated intent to move an isoinertial load as rapidly as possible coupled with performance of the sport-specific movements can promote more efficient coordination and activation patterns. Movement efficiency especially at higher velocities necessitates superior motor control. The development of efficient motor control requires sensory feedback from the musculotendinous system to compare the movement intent with the actual movement execution (Ito 2000; Nixon and Passingham 2001). The cerebellum is integrally involved in movement control and has been labelled as the “grand comparator” as it links and compares the movement intent with the execution of the action and then modifies the subsequent movements based on the disparities between the intent and the actual output to refine and perfect the specified movement (Brooks 1975; Arshavsky et al. 1980; Rasch and Burke 1989; Bhanpuri et al. 2013). The spinocerebellum and vestibulocerebellum receive the sensory inputs from the periphery and vestibular systems, respectively (monitors the action), which then plays a role in modulating the activity of the cerebrocerebellum, which coordinates the planning of movements (the intent) (Brooks

1975; Arshavsky et al. 1980; Rasch and Burke 1989; Bhanpuri et al. 2013). According to Normand et al. (1982), maximum arm speed training help establish cerebellar motor programs to integrate agonist and antagonist contractions during these high velocity movements.

Training activities such as plyometrics blend both the intent to contract explosively and the sensory feedback from the actual movement. Plyometrics are exercises involving repeated rapid stretching and contracting of muscles (e.g., hopping, jumping, sprinting, and rebounding) to increase muscle power (Potach and Chu 2008). Typically, plyometrics with activities such as drop jumps, hurdles, sprinting, and bounding, among others emphasize a short amortization or rebound phase (Potach and Chu 2008; Galay et al. 2020). Thus, the stretch-shortening cycle plays an important role in plyometrics as it does for most other rapid locomotor activities. The primary goal of plyometrics is to enhance the neural and musculotendinous systems to produce maximal power in the shortest duration (Galay et al. 2020). In terms of training specificity, plyometrics provides velocity, contraction type (eccentric and concentric), and movement pattern training specificity, with the ability to transfer these training gains to enhance functional athletic performance (Loturco et al. 2014; Loturco et al. 2015; Ramirez-Campillo et al. 2019).

The effectiveness of plyometric training programs to enhance dynamic performance generally are typically reported to be of small to moderate magnitude in athletic populations. The Ramirez-Campillo group has published several systematic reviews and meta-analyses on the topic. For example, Ojeda-Aravena et al. (2023) examined plyometric training programs of 4–12 weeks and 2–3 sessions per week, reporting small to moderate magnitude improvements in combat athletes' maximal strength (e.g., 1RM squat), vertical jump height, change-of-direction speed, and specific performance (e.g., fencing movement velocity), without significant impacts on body mass, fat mass, or muscle mass. Similarly, a meta-analysis by Sole et al. (2021) reported small magnitude plyometric-induced improvements with vertical jump, sprint speed, maximal strength, and endurance with individual sport athletes (e.g., runners, swimmers, gymnasts, tennis). Garcia-Carillo et al. (2023) analysed 30 upper body plyometric training studies in their meta-analysis, with male and female participants from various sport-fitness backgrounds with training durations ranging from 4–16 weeks. Upper body plyometric training improved maximal strength (small magnitude), medicine ball throw performance (moderate magnitude), sport-specific throwing performance (small magnitude), and upper limbs muscle volume (moderate magnitude), however, according to GRADE analyses the certainty of evidence was low to very low. A meta-analysis of 13 studies (moderate to high methodological quality) found small magnitude, significant effects of plyometric jump training on repeated sprint ability, best and mean sprint times of athletes but no difference between control and plyometric jump training for repeated sprint ability fatigue resistance (Ramirez-Campillo et al. 2021*b*). They attributed these training gains to neuromechanical influences (e.g., strength, muscle activation, and coordination). Another Ramirez-Campillo et al. (2022*b*) meta-analysis of plyometric training effects on water sport athletes showed no effects on in-water vertical jump or agility, body mass, fat mass, and thigh girth but there were moderate-to-large magnitude effects for maximum back squat strength, horizontal jump distance, squat jump, and countermovement jump height.

Similar findings were seen with children as Ramirez-Campillo et al. (2023) reported that plyometric jump training (4–36 weeks, using 1–3 weekly training sessions) provided small to moderate magnitude improvements in maximal dynamic strength, linear sprint speed, horizontal jump performance, reactive strength index, and sport-specific performance (e.g., soccer ball kicking and dribbling velocity). Notably, these improvements were independent of the maturity status, (pre- vs. post-peak height velocity stage). Strength, plyometric, and combined training of high level, male youth soccer players demonstrated moderate magnitude increases in strength, squat and countermovement jump, horizontal power, acceleration, and change of direction speed with small magnitude improvements in sprinting speed (15–40 m) (Oliver et al. 2023). Whereas plyometric training alone induced small magnitude improvements, strength and combined training produced moderate enhancements in lower body strength (Oliver et al. 2023). A plyometric jump training meta-analysis emphasizing effects on balance reported small magnitude effects on dynamic (e.g., Y-balance test) and static (e.g., flamingo balance test) balance irrespective of sex and participants' age, which were comparable to balance training (Ramachandran et al. 2021).

The lack of many large magnitude training effects might be attributed to the athletic populations that were reviewed, who were already in a more highly trained state and thus unlikely to achieve more substantial training adaptations. As plyometrics are a more advanced form of dynamic training, there may be reluctance or hesitancy by some researchers to impose higher velocity, higher power, reactive strength type training on untrained populations due to the possibility of injury or the need for a more prolonged period of familiarization. However, an umbrella review of 29 plyometric meta-analyses found trivial-to-large effects on physical performance for healthy individuals, whereas there were trivial to medium effects for athletes from different sports (Kons et al. 2023). Hence, individuals who are not highly trained may receive larger magnitude training benefits. Notwithstanding, the untrained population must have a basic foundational level of strength and the plyometric program must be carefully progressed to avoid overstress injuries.

Plyometric training mechanisms

Plyometric training-related muscle activation improvements were reported with strength and jumping tasks, while a correlational analysis showed significant positive relationships between increases in muscle activation and jump performance (Ramirez-Campillo et al. 2021*a*). Whereas improvements were reported in 13 of 20 studies, 80% were statistically non-significant compared to control conditions (Ramirez-Campillo et al. 2021*a*); hence, there should be caution about making strong conclusions. According to Taube et al. (2012) plyometric training-induced increases in muscle activation are dependent on drop jump height with increases in concentric muscle activation with high drop jump heights and increases in eccentric muscle activation during lower drop jump heights. It has been suggested that similar to muscle activation changes, that H-reflex activity (afferent excitability of the spinal motoneurons) is drop jump phase dependent and may contribute to injury prevention (Leukel et al. 2008*a*, 2008*b*). Another example of sensory-induced alterations with plyometric training would be the increase in the muscle coactivation during the preparatory phase of landing (Chimera et al. 2004; Wu et al. 2010; Heinecke 2021), which could contribute to improved performance (increased joint stiffness promotes a more rapid elastic rebound due to less compliance) or injury prevention (increased stabilization) (Heinecke 2021). The stretch-shortening cycle can become more efficient with plyometric training as the amortization (transition period or ground contact time) phase has been shown to shorten in duration allowing for a more rapid rebound effect optimizing storage and reutilization of elastic energy (Taube et al. 2012; Hirayama et al. 2017). Activation of the stretch-reflex should enhance the concentric contraction by improving agonist-antagonist reciprocal activation patterns and inducing higher motor unit discharge rates (Galay et al. 2020; Heinecke 2021; Ojeda-Aravena et al. 2023). Once again, this training adaptation is jump height specific as excessive heights result in prolonged amortization or ground contact durations to absorb the excessive ground reaction forces (Heinecke 2021). In addition, plyometric training can induce increases in maximum muscle strength (Saez-Saez de Villarreal et al. 2009; Sole et al. 2021; Ramirez-Campillo et al. 2022*b*, 2023; Ojeda-Aravena et al. 2023).

Plyometric movement (e.g., jumps, bounding, sprinting) is considered ballistic as the definition of ballistic relates to the motion of projectiles (including humans) in flight (online Merriam Webster dictionary). Ballistic contractile movements are characterized by a unique triphasic EMG signal consisting of an initial burst of agonist EMG activity at high firing frequencies (can reach 80–120 Hz) followed by an antagonist activation finishing with another agonist EMG contribution (Roy et al. 1988; Behm and Sale 1993*b*). The first agonist EMG burst serves to initiate a propulsive contractile force, with the second antagonist burst available as a braking and corrective contribution, while the second agonist burst is related to movement velocity and further possibilities for movement corrections (Roy et al. 1988; Behm and Sale 1993*b*). Ives et al. (1999) reported that the increase in the initial agonist EMG activity and the corresponding rate of static force development differed substantially between load and quick release conditions. Hence, ballistic-intent contractions against high resistance or with isometric contractions would induce specific but differing agonist muscle activation patterns versus plyometrics due to the differing anticipation of movement dynamics. Similarly, Lagasse (1979) suggested there are different neuromotor control systems for speed and strength, with a coordination between agonist and antagonist muscles contributing to the production of maximal speed. Normand et al. (1982) had 20 male participants train over 8 sessions for 800 repetitions of maximum speed arm adduction and forearm flexion movements with their results suggesting that a specific motor program resides in the cerebellum for bi-articular movements controlling agonist and antagonist coupling or coordination. Likewise, Almasbakk and Hoff (1996) highlight the development of coordination as the determining factor in early velocity specific gains. In summary, plyometric training can induce neuromuscular alterations in muscle strength, activation, reflex activity, co-contractions, and motor or movement control (i.e., more rapid stretch-shortening cycle) (Fig. 1). However, the neuromuscular training adaptations to ballistic-intent contractions against a high resistance (resulting in an isometric or slow speed contraction) would differ from the adaptations to a plyometric activity, which also involves ballistic-intent but produces a ballistic-like movement (i.e., human projectile moving at higher velocities).

Recommendations

To promote the most effective plyometric training program, a foundation of strength (minimum 4–6 weeks) especially eccentric strength is needed (Ebben and Watts 1998). Without sufficient eccentric strength, the amortization (transition) period of the stretch-shortening cycle is prolonged and the advantage of the elastic recoil of muscle and connective tissue and reflex potentiation is diminished. To develop that foundational strength with high velocity specific adaptations, there is evidence that a ballistic-intent strength training program should be incorporated (Behm and Sale 1993*b*) especially in the off-season. This may be particularly relevant with youth populations that may lack a suitable foundation of strength and hence may be more susceptible to injury (Mersmann et al. 2017). Thus, not only will increased force be developed but the higher frequency motor unit firing will be improved for a higher rate of concentric force development (Behm and Sale 1993*b*).

Plyometric training should be subsequently incorporated to ensure the sensory feedback to monitor and positively alter the stretch-shortening cycle (concentrating on rapid eccentric, transition and concentric phases). A plyometric review for soccer players by Ramirez-Campillo et al. (2022*a*) recommended a minimum of 7 weeks of training (1–2 sessions per week), with ∼80 jumps (specific of combined types) per session, using near-maximal or maximal intensity, with adequate recovery between repetitions (<15 s), sets (30 s) and sessions (24–48 h), with progressive overload and tapering, using appropriate surfaces (e.g., grass), with the athletes training in a well-rested state. The plyometrics should be integrated with other sport-specific training methods, for effective and safe plyometric-jump training interventions. A meta-analysis by Saez-Saez de Villarreal et al. (2009) recommended high-intensity exercises with a training volume of less than 10 weeks, more than 15 sessions, and more than 40 jumps per session, to maximize performance improvements. They also suggested to implement a combination of different types of plyometrics with RT rather than utilizing only one type of plyometric exercise. According to Ebben and Watts (1998) RT, plyometric training and sport-specific exercises should be integrated (complex training) to most effectively transfer training adaptations to specific athletic movements.

Sex differences

A missing ingredient in many sport science papers is the under-representation of females in the study groups as well as their contributions as research authors. Mujika and Taipale (2019) in an editorial reported that less than 40% of participants in three major sport science journals were women. However, in this ballistic-intent literature, there were only 21% more male than female participants in the cited studies, however, in the plyometric literature there is a greater discrepancy. Not all ballistic-intent studies analyzed sex differences since, for example, several studies recruited only female (e.g., Ryan et al. 1991; Almasbakk and Hoff 1996; Cronin et al. 2001) or only male (e.g., Moss et al. 1997; Coyle et al. 1981; McDonagh et al. 1983) participants or did not have matched numbers of participants (e.g., Moffroid and Whipple 1970). While Behm and Sale (1993*a*) recruited eight males and females, they did not find any significant sex differences with their 16-week training program. On the other hand, Ives et al. (1993) reported males to have faster movements through the full range of motion and accelerations and faster rates of EMG rise, They postulated that the females were more neurally constrained (rapid EMG activation of the triceps brachii) resulting in limits in the braking process. More research is needed to highlight possible sex differences.

Conclusions

As many sports incorporate explosive movements with high force and power outputs, the neuromuscular system must be prepared for these actions. RT for maximal strength, hypertrophy or even as preparation for plyometrics should emphasize ballistic or explosive intent contractions to ensure the corticospinal system is consistently subjected to initial high velocity muscle contractions even if the resistance or load culminates in a slow movement. Since high velocity movements are typically multi-articular and necessitate high coordination, the combination of explosive intent and high-speed actions with plyometrics provides a rich sensory environment from which the neuromuscular system (cortical, spinal, and muscle) can optimize motor learning. While a foundation of strength is needed prior to implementing a plyometric training program, both can be incorporated simultaneously within complex training programs to enhance post-activation potentiation effects (Blazevich 2012; Blazevich and Babault 2019).

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