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Section III – Sports Training

Vertical Jumping as a Monitoring Tool in Endurance Runners: A Brief Review

by

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Jumping performance (e.g., countermovement jump [CMJ]), as a measure of neuromuscular performance, has been suggested as an easy-to-use tool which simultaneously provides neuromuscular and metabolic information and, thereby, allows coaches to confidently monitor the status of their athletes during a workout. This hypothesis has been satisfactorily tested with sprint athletes. However, the rationale for the use of CMJ height loss as an index to monitor the workload during an endurance running session is not sufficiently evidence-based. First, it is assumed that a CMJ height loss occurs during typical interval training for endurance runners. Second, it is also assumed that a significant relationship between metabolic stress and the neuromuscular strain induced during these endurance workouts exists. These two assumptions will be questioned in this review by critically analyzing the kinetics of CMJ performance during and after running workouts, and the relationship between neuromuscular and physiological stress induced during different protocols in endurance runners. The current evidence shows that fatigue induced by common running workouts for endurance runners does not counterbalance the potentiation effect in the CMJ height. Additionally, the findings reported among different studies are consistent regarding the lack of association between CMJ height loss and physiological stress during interval sessions in endurance runners. In practical terms, the authors suggest that this marker of neuromuscular fatigue may not be used to regulate the external training load during running workouts in endurance runners. Nevertheless, the analysis of CMJ height during running workouts may serve to monitor chronic adaptations to training in endurance runners.

***Key words**: post activation potentiation, dose-response, individualization, fatigue.*

Introduction

As coaches of endurance runners, we can prescribe a load (i.e., external load) in terms of the volume (e.g., distance or time) at a given intensity (e.g., power or speed) to accumulate work at any intensity zone in the pursuit of a specific target. Then, we can analyze the impact induced by that training load on the athlete´s organism (i.e., internal load). The internal load determines how the athlete adapts to the training session (Impellizzeri et al., 2019), and it can be measured at: i) the metabolic level such as the concentration of metabolites which provides information about the implication of metabolic pathways demanded and energetic stores available (Del Coso et al., 2013), ii) the autonomic level such as the activity of the central nervous system through the heart rate (Achten and Jeukendrup, 2003) and its

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variability (Plews et al., 2013), iii) the neuromuscular level including the force production capacity or muscle soreness (Claudino et al., 2017), or iv) the psychological level considering the rate of perceived exertion (RPE) and readiness scales (Grove et al., 2014), among others. All these monitoring tools have their advantages and drawbacks, and different approaches have been previously proposed, mostly based on the combination of various methods (Bourdon et al., 2017; Foster et al., 2001; Halson, 2014).

When coaches try to optimize the dose of training for a specific athlete with a particular goal, the available monitoring tools appear to be quite limited. For instance, how do coaches determine the optimal training volume during an interval running session? Is it prefixed or individually adapted to the individual work capacity of the athlete at that intensity and that time? Regarding this, previous studies have examined the sensitivity of vertical jump performance to detect neuromuscular fatigue during continuous (Boullosa et al., 2009, 2011; Del Coso et al., 2012, 2013; Rousanoglou et al., 2016) and interval running sessions (Gorostiaga et al., 2010; Morcillo et al., 2015; Vuorimaa et al., 2006) in endurance trained athletes using the countermovement jump (CMJ), which has been suggested to be the most reliable and suitable monitoring tool for this purpose in different settings (Gathercole et al., 2015). In this context, the use of the CMJ for monitoring the athletes' responses and thus deciding when the running session should be interrupted might be suggested. Therefore, this review aimed to examine the validity and practicality of the CMJ as a monitoring tool during different running exercises with endurance athletes.

Where does this approach come from? Is it evidence-based?

Some previous studies (Bachero-Mena et al., 2020; Gorostiaga et al., 2010; Jiménez-Reyes et al., 2013, 2016, 2019) monitored CMJ performance over different running sessions for sprinters and those authors concluded that monitoring CMJ height may allow a more accurate setting of training loads during this type of workouts using an individualized dose rather than a fixed number of repetitions. In the current review, we analyzed the potential application of monitoring CMJ performance during typical running sessions in endurance athletes. We also suggest that the attempt to literally transfer the findings obtained in those previous studies with sprinters, during workouts not typically included in training of endurance runners, may induce misinterpretation.

Therefore, the potential application of CMJ monitoring for deciding when to interrupt an endurance running session in order to individualize the training load is based on two questionable assumptions extracted from the aforementioned studies (Bachero-Mena et al., 2020; Gorostiaga et al., 2010; Jimenez-Reyes et al., 2013, 2016, 2019). First, it is assumed that the CMJ height loss occurs during typical interval training for endurance runners in the same way as it has been observed with sprinters (Gorostiaga et al., 2010; Jimenez-Reyes et al., 2013, 2016, 2019) and 800-m athletes (Bachero-Mena et al., 2020). Secondly, it is also assumed that a significant relationship between physiological stress and the neuromuscular strain induced during endurance workouts exists since that relationship was strong and significant in sprinters. These two assumptions will be questioned and examined for endurance runners in the next sections.

Jump height loss during running events. Does it even happen?

Findings of previous studies revealed that the effects of continuous vs. interval training sessions on CMJ performance are controversial (Table 1). While some studies have reported reductions in jumping height after a marathon (~13%, Nicol et al., 1991, and ~22%, Del Coso et al., 2013), a half-marathon mountain race (4.1-7.9%, Rousanoglou et al., 2016) and after a half-ironman triathlon (~23%, Del Coso et al., 2012), one study did not find a reduction in CMJ height immediately after a simulated sprint-distance triathlon (García-Pinillos et al., 2015). Moreover, another study (Vuorimaa et al., 2006) reported an improvement (8.5%) in CMJ performance immediately after 40-min of a continuous run at an intensity of 80% of velocity associated with maximal oxygen uptake (VO_{2max}) in elite endurance runners. Furthermore, Del Rosso et al. (2016) observed an enhancement in CMJ height during a 30-km trial in well-trained distance runners (14%).

Previously, Boullosa and colleagues (2009, 2011) examined the effect of two exhausting in-field protocols, the University of Montreal Track Test and the time limit test at maximum aerobic speed, on CMJ performance. Those authors found an increment in jumping height after both running protocols (12.7% and 4.9%, Boullosa and Tuimil, 2009; and 3.6%, Boullosa et al., 2011). Likewise, in a related study (García-Pinillos et al., 2018), a group of endurance runners completed the Léger-Lambert test and the CMJ height was also improved (5.5%). In line with other studies (Boullosa et al., 2018; Wilson et al., 2013), these works highlight that there are several factors which could mediate the effect of running sessions on jumping capacity (e.g., neuromuscular evaluation methods, running protocol or recovery time), but the authors suggested that an elastic energy enhancement might explain the improvement in CMJ height after running under the tested conditions.

Given the lack of consensus between those previous studies, it seems justified to further examine the effect of the potential mediators on the balance between potentiation and fatigue influences after a running protocol, which could be the intensity of the running exercise (i.e., maximal vs. submaximal) and the training background of the athletes (i.e., sprinters vs. endurance runners). Previously, Jiménez-Reyes et al. (2016, 2019) examined the acute effect of two different habitual training routines for sprinters on metabolic (i.e., blood lactate and ammonia) and neuromuscular variables (i.e., CMJ and sprint performance). The protocols consisted of: (i) 40-m maximal sprints with 4 min rest intervals between sets until sprint performance decreased by 3% (Jimenez-Reyes et al., 2016), and (ii) 60-m maximal sprints with 6 min rest intervals between sets, up to a 3% speed loss (Jiménez-Reyes et al., 2019). After both protocols, ~14-16% impairment of CMJ performance was observed thus supporting the use of CMJ height as a tool for monitoring sprint training and quantifying mechanical and metabolic fatigue (Jiménez-Reyes et al., 2013). A more recent study with 800-m athletes (Bachero-Mena et al., 2020) reported similar results during a typical high-intensity training session based on 5 × 200 m with a 4 min rest interval. Similarly, another study (Morcillo et al., 2015) tested the acute effect of repeated sprints on vertical jump performance and the results were consistent with the data above. Meanwhile, what does occur during interval running sessions at submaximal intensities? Does CMJ performance decrease with the onset of and increases in fatigue? The current evidence does not support such a decrease. Furthermore, although the evidence might seem surprising, it is consistent. Two different studies by García-Pinillos et al. (2015, 2016) described the acute effects of three different high-intensity interval running sessions on jumping performance in endurance runners: (i) 12 runs of 400 m (4 sets of 3 runs) with a passive recovery of 1 min between runs, and 3 min between sets (4 × 3 × 400 m) (García-Pinillos et al., 2015); (ii) 10 runs of 400 m with 90 s of recovery (10 × 400 m) (García-Pinillos et al., 2016); (iii) 40 runs of 100 m with 30 s of recovery (40 × 100 m) (García-Pinillos et al., 2016). None of those protocols reduced CMJ height in endurance runners, despite high levels of the RPE (~17) and blood lactate (~13 mmol/l). In fact, the results showed a CMJ performance enhancement after the 4 × 3 × 400 m protocol (7.89%) (García-Pinillos et al., 2015), and after the 10 × 400 m protocol (5.18%) (García-Pinillos et al., 2016), whereas the CMJ height remained stable during the 40 × 100 m protocol. Another previous study (Vuorimaa et al., 2006) also examined the effect of an interval running workout on CMJ height in trained endurance runners based on alternating 2 min at 100% of velocity associated with VO_{2max} and 2 min of recovery. An increase in jumping height after each running bout was reported thus reinforcing the notion that CMJ height is not reduced during high-intensity interval running protocols at submaximal intensities. In fact, most of those previous studies (García-Pinillos et al., 2015, 2016; Vuorimaa et al., 2006) did not find any impairment in CMJ height during the running session, but an improvement in vertical jump performances despite high levels of central and peripheral fatigue (i.e., when considering the RPE and blood lactate responses).

Therefore, according to the current evidence, it seems that, when running speed is maximal (e.g., sprint interval session), a CMJ height loss would be expected. However, during submaximal running bouts (e.g., high-intensity intermittent sessions) for endurance runners, CMJ performance remains unchanged or even is improved. Although there is not a single explanation for that phenomenon, there are a number of potential justifications. On the one hand, there is a direct relationship between phosphocreatine resynthesis following intense exercise and maximal oxygen uptake (McMahon and Jenkins, 2002), and the adaptations of the muscle cells to endurance training showing an increased content of fast myosin light chains in type I muscle fibers (Hamada et al., 2000). This might explain the between-athlete differences in response to endurance running protocols. On the other hand, it has been suggested that a faster running pace imposes higher neural demands, which may lead to a failure to fully activate the contracting musculature in the subsequent activity (Ross et al., 2001), because the higher intensities during training protocols would induce the recruitment of additional fast-twitch motor units for relatively short duration (Enoka and Duchateau, 2008).

Consequently, such findings reinforce the notion that CMJ height may not be an adequate marker of internal training loads during this type of workouts in endurance runners lacking its sensitivity to help in the regulation of the external training load. Moreover, based on previous research (Boullosa et al., 2011; García-Pinillos et al., 2015), the authors would suggest that the analysis of mechanical variables and force-time relationships during vertical jumping might be more useful.

Post-activation performance enhancement during running protocols

As already mentioned, previous studies have demonstrated the lack of reduction in CMJ height during high-intensity intermittent running protocols in endurance athletes, despite high levels of perceptual and metabolic fatigue. These specific responses of endurance runners may be understood when considering the post-activation performance enhancement (PAPE) phenomenon which refers to the improvement of muscular performance as a result of previous muscular work (Blazevich and Babault, 2019). In this context, when endurance athletes experience post-running jump potentiation (Boullosa et al., 2020), this means that the level of muscle potentiation is greater than neuromuscular fatigue associated with the running exercise.

After muscular work is completed in a conditioning protocol, mechanisms of muscular fatigue and PAPE coexist with subsequent mechanical power output and performance depending on the balance between these two factors. As recently indicated by Boullosa et al. (2018), PAPE practices have been traditionally associated to maximal intensity and short duration efforts (i.e., power demanding sports) (Bachero-Mena et al., 2020; Jiménez-Reyes et al., 2013, 2019), whereas endurance practitioners are unaware of the potential of this phenomenon to optimize endurance performance in both training and competition settings.

Generally, PAPE is not expected to occur after prolonged running in the presence of high levels of fatigue. However, as previously mentioned, CMJ improvements have been also reported after prolonged continuous runs (García-Pinillos et al., 2015; Rousanoglou et al., 2016; Vuorimaa et al., 2006), incremental running protocols to exhaustion (Boullosa et al., 2009, 2011; García-Pinillos et al., 2018), and after high-intensity intermittent running exercises (García-Pinillos et al., 2015, 2016; Vuorimaa et al., 2006). Although there are different proposed mechanisms, most studies from animal to human models (Boullosa et al., 2018; Hamada et al., 2000; Wilson et al., 2013) suggest the regulatory myosin light chain phosphorylation as the prominent underlying mechanism (Grange et al., 1993). It is known that endurance training simultaneously induces phosphorylation of regulatory myosin light chains in slow-twitch fibers and resistance to fatigue, which may explain the typical PAPE responses observed in endurance athletes after endurance running exercises (Boullosa et al., 2018; Hamada et al., 2000). Currently, there are some gaps in the literature about the effective practical applications of the PAPE phenomenon in the training context of endurance runners and thereby some uncertainty among endurance coaches have been raised. Meanwhile, it seems clear that the presence of PAPE during interval workouts of endurance runners makes CMJ height loss a useless index of the internal load in terms of determining when the external training load should be reduced or stopped as it would occurs with power trained athletes.

Table 1a.

Studies examining the effects of different running protocols on countermovement jump (CMJ) performance and mechanical variables.

Reference	Subject description	Aim	Outcome measures	Results
Boullosa and Tuimil (2009)	12 well-trained endurance runners	To compare jumping capacity after two different running protocols: - UMTT - Tlim at MAS	CMJ height pre- and post-tests (2nd and 7th min of recovery).	CMJ height enhanced during the fatigued conditions with jump height greater at the 2nd min of recovery after both protocols (+12.7% and +4.9%).
Boullosa et al. (2011)	22 endurance athletes	To examine the concurrent fatigue and PAP in endurance athletes after an incremental field running test (UMTT)	CMJ height pre- and post-test and mechanical variables (i.e, power and force). 20 m sprint performance. BLa concentration.	CMJ height enhanced immediately after the running protocol (+3.6%), with an increment in peak power (+3.4%) and a concurrent peak force loss (-10.8%).
Del Coso et al. (2013)	40 amateur endurance runners	To determine the causes of running fatigue during a marathon in warm weather	CMJ height pre- and post-test and mechanical variables (i.e, power and force). Blood and serum responses.	CMJ height and peak power during the concentric phase were reduced within 3 min after a marathon (-17.8% and -21.8%, respectively).
Del Coso et al. (2012)	25 trained triathletes	To investigate the causes of muscle fatigue experienced during a half-iron distance triathlon	CMJ height pre- and post-test and mechanical variables (i.e, power and force). Blood and serum responses.	Reductions in jumping height and peak power during the concentric phase within 3 min after a half-iron triathlon (22.8% and 19.1%, respectively).
García-Pinillos et al. (2015)	19 triathletes	To describe the acute impact of a simulated sprint-distance triathlon at physiological and neuromuscular levels	CMJ, SJ and HS were tested at pre- and post-test and during every transition.	No changes in jumping height immediately after a simulated sprint-distance triathlon.
García-Pinillos et al. (2016)	18 amateur endurance runners	To describe the acute effects of 2 different running sessions (10 x 400 m and 40 x 100 m) on postural control, CMJ, SJ and SSC utilization, and to compare the changes induced by both protocols in those variables in endurance runners	Vertical jump height and postural control.	CMJ performance improved immediately after the 10 × 400 m protocol (+5.18%), whereas the CMJ height remained unchanged after the 40 × 100 m protocol.
García-Pinillos et al. (2018)	33 amateur endurance runners	To analyze the acute effects of an incremental running test (Leger Test) on CMJ and HS performance in endurance athletes, considering the effect of post-exercise recovery time and sex	CMJ height and mechanical variables pre- and post-tests (1st, 5th and 10th min of recovery).	CMJ height improved 1 min after the running protocol (+5.5%).

UMTT: Université de Montréal Track Test; Tlim: time limit test; MAS: maximal aerobic speed; CMJ: countermovement jump test; PAP: post-activation potentiation; BLa: blood lactate; SJ: squat jump; HS: handgrip strength; SSC: stretch-shortening cycle

Table 1b.

A continuation of Table 1 - Studies examining the effects of different running protocols on countermovement jump (CMJ) performance and mechanical variables.

Reference	Subject description	Aim	Outcome measures	Results
García-Pinillos et al. (2015)	30 endurance runners	To analyze effects of a running protocol (4 x 3 x 400 m) on CMJ and HS performance in endurance athletes.	CMJ height pre- and post-test and BLa response.	Improvement in CMJ height immediately after the 4 × 3 × 400 m protocol (+7.89%)
Jimenez-Reyes et al. (2016)	9 high-level sprinters	To quantify muscular fatigue while performing a sprint training session (40 m maximal running with 4 min in-between until sprint performance decreased by 3%).	CMJ height, speed loss and metabolic responses (i.e. BLa and ammonia concentrations) were measured pre-exercise, during exercise and post-exercise.	14% impairment of CMJ height (measured immediately after the protocol) for the 3% of speed loss condition.
Jimenez-Reyes et al. (2019)	9 high-level sprinters	To analyze the acute mechanical and metabolic responses to a sprint training session (i.e., 60 m maximal running with 6 min of recovery up to a 3% speed loss).	CMJ height, speed loss and metabolic responses (i.e. BLa and ammonia concentrations) were measured pre-exercise, during exercise and post-exercise.	16% impairment of CMJ performance (measured immediately after the protocol) for the 3% of speed loss condition.
Morcillo et al. (2015)	18 professional soccer players	To analyze the acute metabolic and mechanical responses to a specific RSA test (12 × 30-m sprint test with 30 s recovery).	Mechanical responses (i.e., CMJ and speed loss) and metabolic responses (i.e., BLa and ammonia) were evaluated before and after exercise.	Reduction of 8% in CMJ height (pre-post comparison, measured immediately after the protocol).
Nicol et al. (1991)	9 endurance runners	To determine the fatigue effects of running a marathon on neuromuscular performance.	Neuromuscular performance tests through force plate and dynamometer techniques (pre-, during and post-running).	Reductions in jumping height after a marathon (-13%, measured immediately after running).
Del Rosso et al. (2016)	11 endurance runners	To assess the influence of PAP on pacing, jumping and other physiological measures during a self-paced 30 km trial.	CMJ height and BLa response pre-, during and post-running.	Enhancement in CMJ height immediately after a 30 km trial in well-trained distance runners (+14%).
Rousanoglou et al. (2016)	27 endurance runners	To investigate the alterations of CMJ mechanics after a half-marathon mountain race.	CMJ height and mechanical variables before the race, immediately after and 5 min after.	Not statistically significant (4.1%) reduction in jump height immediately after the race, but significant reduction 5 min post (-7.9%).
Vuorimaa et al. (2006)	22 trained endurance runners	To investigate the acute changes in muscle activation and performance after 3 protocols in runners: - Incremental running test until exhaustion - 40 min continuous run - 40 min intermittent running (2 min at 100% VO_{2max} and 2 min of recovery at 80%)	CMJ height and mechanical variables pre- and post-tests. BLa concentrations.	The CMJ height increased immediately after the 3 protocols performed (+5.6-8.5%).

PAP: post-activation potentiation; BLa: blood lactate; SJ: squat jump; HS: handgrip strength; SSC: stretch-shortening cycle; RSA: repeated sprint ability; VO_{2max}: maximum oxygen uptake

Table 2a.
Studies examining the relationship between neuromuscular strain, in terms of CMJ performance, and metabolic stress during different training protocols.

Reference	Subject description	Training protocol/s	Outcome measures	Results
Bachero-Mena et al. (2020)	9 male high-level 800-m runners	5 x 200 m with 4 min rest intervals	CMJ height, speed loss and metabolic responses (BLa) were measured pre-exercise, during exercise and post-exercise	A significant negative relationship ($p < 0.001$; r = -0.83) was found between the individual values of jumping height and blood lactate concentration.
García-Pinillos et al. (2015)	30 endurance runners	An interval running session: - 4 x (3 x 400 m) with 1 min between runs and 3 min between sets	CMJ height and related mechanical variables, and BLa were measured before, during and after the protocol	No correlation/association analysis between neuromuscular and metabolic variables. A 7.89% improvement in CMJ height after the protocol was found despite an accumulating high level of BLa (13.8 mmol/l) and the RPE (18).
García-Pinillos et al. (2016)	18 amateur endurance runners	Two different interval running sessions: - 10 x 400 m with 90 s recovery - 40 x 100 m with 30 s recovery	Vertical jump height, postural control and BLa were evaluated before, during and after the protocol	No correlation/association analysis between neuromuscular and metabolic variables. A 5.18% improvement in CMJ height after the running protocol, despite high levels of lactate (12.9 mmol/l) and the RPE (16).
Gorostiaga et al. (2010)	12 400-m elite male runners	Six interval running sessions: - 3 x 60 m with 4 min recovery + 3 x 80 m with 6 min recovery + 3 x 100 m with 8 min recovery - 6 x 100 m with 5 min recovery - 8 x 200 m with 3 min recovery - 6 x 300 m with 6 min recovery - 3 x (3 x 300 m) with 4 min between runs and 8 between sets - 12 x 300 m with 3 min recovery	CMJ height and metabolic responses (BLa and BAmm) were measured pre-exercise, during exercise and post-exercise	Significant curvilinear negative relationship between BLa and BAmm concentrations and jumping height ($p < 0.05$; R^2=0.68 and 0.51, respectively).

BLa: blood lactate; BAmm: blood ammonia; CMJ: countermovement jump test; RPE: rate of perceived exertion; VO_{2max}: maximum oxygen uptake

Table 2b.

A continuation of Table 2 – Studies examining the relationship between neuromuscular strain, in terms of CMJ performance, and metabolic stress during different training protocols.

Reference	Subject description	Training protocol/s	Outcome measures	Results
Jimenez-Reyes et al. (2016)	9 high-level sprinters	A sprint interval training session: - 40 m maximal running with 4 min recovery until sprint performance decreased by 3%.	CMJ height, speed loss and metabolic responses (BLa and BAmm) were measured pre-exercise, during exercise and post-exercise.	Inverse relationship between CMJ height and metabolic measures (BLa and BAmm) (r = 0.95-0.96).
Morcillo et al. (2015)	18 professional soccer players	A sprint interval training session: - 12 × 30-m sprint test with 30 s recovery	Mechanical responses (i.e., CMJ height and speed loss) and metabolic responses (i.e., BLa and BAmm) were measured before and after exercise.	Inverse relationship between CMJ height and metabolic measures (BLa and BAmm) (r = 0.92-0.97).
Sanchez-Medina et al. (2011)	18 strength-trained males	Different resistance exercise protocols differing in the number of repetitions performed and loads.	Mechanical data were measured by a linear velocity transducer during lifting and metabolic responses (BLa and BAmm) were measured before and after exercises.	Significant relationship between the CMJ height loss and the metabolic response (BLa and BAmm) during different resistance exercise protocols (r = 0.93-0.97).
Vuorimaa et al. (2006)	22 trained endurance runners	Three different running exercises: - Incremental running test until exhaustion - 40 min continuous running at 80% VO_{2max} - 40 min intermittent running (2 min at 100% VO_{2max} and 2 min walking)	CMJ height and mechanical variables were evaluated pre- and post-tests, while BLa concentrations before, during and after the protocols.	No correlation/association analysis between neuromuscular and metabolic variables. An improvement in CMJ height after the running protocols (+8-14%) was found, despite high levels of lactate (~11 mmol/L, ~4 mmol/L and ~7 mmol/L, for the aforementioned protocols, respectively)

BLa: blood lactate; BAmm: blood ammonia; CMJ: countermovement jump test; RPE: rate of perceived exertion; VO_{2max}: maximum oxygen uptake

Does neuromuscular strain correlate with metabolic stress responses during endurance running?

Previous studies with different populations (Bachero-Mena et al., 2020; Gorostiaga et al., 2010; Sánchez-Medina and González-Badillo, 2011) found an almost perfect correlation between CMJ height loss and metabolic stress (e.g. blood lactate concentration) after different training protocols (Table 2). Previously, Sanchez-Medina et al. (2011) identified a strong and significant relationship between mechanical (i.e., CMJ height loss) and metabolic response (i.e., blood lactate and ammonia concentrations) during different resistance exercise protocols (r = 0.93-0.97). Likewise, similar results have been reported during different sprint-based running protocols with athletes simultaneously impairing their CMJ performance while increasing blood lactate and ammonia levels during testing trials. More recently, Bachero-Mena et al. (2020) reported a negative relationship (p < 0.001, r = -0.083) between the individual values of jumping height and blood lactate concentration, whereas Gorostiaga et al. (2010) found a significant curvilinear negative relationship between the individual blood lactate and ammonia concentrations and jumping height ($p < 0.05$; R^2 = 0.68 and 0.51, respectively) during typical workouts for elite 400-m runners. Furthermore, Jiménez-Reyes et al. reported in a number of studies (2013, 2015, 2016, 2019) an inverse relationship between CMJ height and metabolic measures of fatigue after different sprint-based running protocols in which athletes impaired CMJ performance and increased blood lactate and ammonia concentrations (r = 0.92-0.99 for all cases). Thus, these aforementioned studies suggested the use of CMJ height as a tool for monitoring sprint training and quantifying mechanical and metabolic fatigue. However, it was unclear whether those findings may be extrapolated to the neuromuscular and metabolic responses of endurance runners during workouts.

Subsequent studies with endurance athletes (García-Pinillos et al., 2015, 2016; Vuorimaa et al., 2006) examined the acute metabolic and neuromuscular response of different high-intensity intermittent running protocols and found that, despite the high levels of fatigue, the CMJ height was not impaired but even potentiated. For instance, a previous study (García-Pinillos et al., 2015) reported a 7.89% improvement in CMJ height after 12 repetitions of a 400 m run despite accumulating a high level of blood lactate (i.e., 13.8 mmol/l) and a near maximum RPE score (i.e., 18.3). Likewise, another study in endurance runners (García-Pinillos et al., 2016) found a 5.18% increase in CMJ height after an interval running protocol even in the presence of high blood lactate concentrations (i.e., 12.9 mmol/l) and RPE values (i.e., ~16). Therefore, the current evidence suggests that neuromuscular strain does not exhibit an association with metabolic stress during running protocols in endurance runners. Therefore, monitoring CMJ height loss to estimate metabolic stress during endurance workouts seems unfeasible for this population.

The present review aimed to critically analyze the literature regarding the use of CMJ height as a tool to monitor the internal load among endurance runners during running sessions for the manipulation of an athlete's external load. Current evidence shows that fatigue induced by common running workouts of endurance runners does not counterbalance the potentiation effect on CMJ height. Additionally, findings reported in different studies are consistent regarding the lack of association between CMJ height loss and metabolic stress during high-intensity interval running sessions in endurance runners.

Conclusions

The current review highlights the lack of sensitivity of CMJ height as an index of the internal training load during training sessions in endurance runners. Consequently, the authors suggest that this marker of neuromuscular fatigue should not be used to regulate external training loads under these circumstances. Nevertheless, the analysis of CMJ height during running workouts which reflects the balance between inhibition and potentiation may be useful to monitor chronic adaptations to training of endurance runners (Boullosa et al., 2018). As an example, when a runner jumps higher in subsequent sessions with the same running bout, this would mean that the runner has lower fatigue and/or more PAPE thus reflecting therefore positive chronic adaptations. However, this expected adaptation needs to be tested in further longitudinal studies. In this regard, it is advisable to use the novel potentiation taxonomy suggested by Boullosa and colleagues (2020). This new taxonomy proposes the formula "Post-[CONDITIONING ACTIVITY] [VERIFICATION TEST] potentiation in [POPULATION]". This classification would avoid erroneous identification of isolated physiological attributes and provide individualization and better applicability of conditioning protocols in sport settings. For instance, precise identification of jump potentiation during high-intensity intermittent sessions may be understood as follows: post aerobic-intervals CMJ potentiation in male and female endurance runners.

Unfortunately, up to date, there is no single marker which allows a comprehensive picture to be used by coaches to identify the optimal external load during training sessions for maximizing training adaptation in endurance athletes. A flexible training program based on the continuous communication between coaches and athletes which takes into consideration the use of different tools for detecting changes in athletic performance and physiological responses seems to be the best approach for modulating the external training load.

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