Review

A Brief Review of Selected Biomechanical Variables for Sport Performance Monitoring and Training Optimization

Jernej Pleša [1], Žiga Kozinc [2,*] and Nejc Šarabon [2,3,4]

1   Faculty of Health Sciences, University of Primorska, Polje 42, SI-6310 Izola, Slovenia; 97200425@student.upr.si
2   Andrej Marušič Institute, University of Primorska, Muzejski trg 2, SI-6000 Koper, Slovenia; nejc.sarabon@fvz.upr.si
3   Human Health Department, InnoRenew CoE, Livade 6, SI-6310 Izola, Slovenia
4   Laboratory for Motor Control and Motor Behavior, S2P, Science to Practice, Ltd., Tehnološki Park 19, SI-1000 Ljubljana, Slovenia
*   Correspondence: ziga.kozinc@fvz.upr.si

Abstract: Traditional neuromuscular tests (e.g., jumping and sprinting tasks) are useful to assess athletic performance, but the basic outcomes (e.g., jump height, sprint time) offer only a limited amount of information, warranting a more detailed approach to performance testing. With a more analytical approach and biomechanical testing, neuromuscular function can be assessed in-depth. In this article, we review the utility of selected biomechanical variables (eccentric utilization ratio, force–velocity relationship, reactive strength index, and bilateral deficit) for monitoring sport performance and training optimization. These variables still represent a macroscopic level of analysis, but provide a more detailed insight into an individual's neuromuscular capabilities, which can be overlooked in conventional testing. Although the aforementioned "alternative" variables are more complex in biomechanical terms, they are relatively simple to examine, with no need for additional technology other than what is already necessary for performing the conventional tests (for example, even smartphones can be used in many cases). In this review, we conclude that, with the exception of the eccentric utilization ratio, all of the selected variables have some potential for evaluating sport performance.

Keywords: bilateral deficit; eccentric utilization ratio; force–velocity relationship; reactive strength index

1. Introduction

With the fast development of sport science, sport diagnostics is becoming indispensable component of competitive sport for injury prevention performance enhancement and training optimization. Evaluation of athletic performance provides coaches and athletes with information and feedback about an individual's neuromuscular function, which enables insight into the athlete's weaknesses and strengths, based on which individual training plan can be individually tailored. In addition, by repeating diagnostic tests on a regular basis, we can gain insight about the effectiveness of the current training program and decide about further training adjustments. In the strength and conditioning field, strength and power are the most commonly tested neuromuscular capabilities, owing to their significant impact on sport performance [1,2], as well as on injury prevention [3,4]. Maximal strength is evaluated with maximal voluntary contractions (MVC), performed in static/isometric [5,6] or dynamic/isokinetic conditions [7,8], and are widely used for the determination of returning to sport after an injury [9]. While the dynamometers are usually part of laboratory-based testing, strength can be also evaluated through field-based tests, such as repetition maximum testing (RM), that involve the athlete lifting as much weight as possible for one or more repetitions in different movement tasks (i.e., squat, deadlift, bench press). RM testing has been an important component in strength and conditioning practice for evaluating the strength capacity and tailoring individually based weight

training [10]. Moreover, velocity-based methods can be used to estimate maximal strength, without the need to perform repetitions to failure. Based on the velocity of the submaximal weighted specific movement (e.g., squat, bench press, etc.), 1RM can be predicted [11]. Using the velocity-based method for evaluating maximal strength seems to be safer and more time-efficient than traditional RM testing.

In addition to maximal strength, explosive strength and power are important aspects of neuromuscular function for successful sport performance [1], and are usually tested through sport-specific movements, such as sprints, jumps, and throws. Vertical jump assesses the anaerobic power of the lower extremities, and is thus frequently used for sports training [12] and to monitor athletes' neuromuscular performance [13]. The gold standard to evaluate jumping power includes different forms of jumps performed on a force plate [14–16]. Studies report that vertical jumping performance is associated with many movement tasks, such as change in direction (CoD) ability [17,18] and linear sprinting performance [19,20]. Furthermore, jumping tests are also useful for detecting inter-limb asymmetry, which is reported as an important risk factor for injuries and can negatively affect athletic performance [21–23]. Sprints are often used in sport performance testing protocol for assessing the acceleration ability [24,25] and maximal velocity [26]. The literature suggests that the ability to generate large magnitudes of ground reaction force in the horizontal direction is an important component of acceleration performance [27]. While success within sprinting events relies heavily on both the ability to accelerate rapidly and through achieving and maintaining high running velocities [28], studies are also reporting the importance of horizontal force development for CoD performance [29] and sport-specific jumping ability [30]. Based on these observations, sprints over 10–30 m are usually performed for testing and training purposes. Furthermore, for team sport athletes, CoD ability has also been extensively evaluated. There are many different tests to evaluate CoD ability; a recently adopted method in the literature is called CoD deficit, which is suggested to provide a more isolated measure of CoD performance [31]. In brief, the CoD deficit represents the additional time that an athlete requires to complete a CoD task compared to a linear acceleration of the equal distance.

The aforementioned tests (jumps, sprints, 1RM tests, and CoD tests) present useful methods to assess athletic performance, but the basic outcomes (e.g., jump height, peak power, sprint time, 1RM), offer only a limited amount of information, thus warranting a more detailed approach to performance testing. With a more analytical approach and biomechanical testing, neuromuscular function can be assessed in-depth. Such approaches provide more detailed insight into an athlete's neuromuscular capacity and could offer the opportunity for training optimization. An example could be the aforementioned CoD deficit, which enables us to evaluate a more isolated measure of CoD performance, independent of acceleration ability and maximal velocity component (73). Based on the acquired information, the training can be adjusted towards acceleration ability or CoD technique, depending on what the individual is lacking. Previous research has identified several biomechanical variables that could be used in alternative biomechanical testing, such as the reactive strength index (RSI), variables from the force–velocity relationship (FV) in different movement tasks, the eccentric utilization ratio (EUR), and bilateral deficit (BLD). In those selected variables, we systematically change some subcomponents (e.g., load in FV relationship; inclusion of eccentric part in EUR; unilateral performance compared to bilateral performance in BLD; drop height in RSI) of selected movements that are very similar to each other. This allows for an analysis that is still at the macroscopic behavior level, but could provide more detailed insight into an individual's neuromuscular function and physical status, which can be overlooked in conventional testing.

Although the aforementioned "alternative" variables are more complex in biomechanical terms, they are mostly relatively simple to analyze, with no need for additional technology beyond what is already necessary for performing the conventional tests. Despite the selected variables being widely described in scientific literature, to our knowledge, there is no review that synthesizes their relevance to sport performance and training op-

timization to help coaches select sport diagnostics tools that would be sensible for more detailed training adjustments. The aim of this review is to cover some of the biomechanical variables that are frequently mentioned/justified in scientific literature but are still not commonly used in practice. Based on that, we examine the associations between selected biomechanical variables and sport performance and its usefulness for training-related decision making for improving performance.

2. Eccentric Utilization Ratio

The most commonly used method for assessing the explosive power of lower limbs are different types of jumps [32]. Two of the most frequently used vertical jumps for assessment purposes are the squat jump (SJ) and the countermovement jump (CMJ) [12]. On average, the height of the CMJ is 5–15% higher than CMJ [33]. This ratio between the jumps has been termed as "eccentric utilization ratio" (EUR) (i.e., CMJ height divided by SJ height), and has been often purported to serve as an indicator of performance [34]. It should be also mentioned that a few different calculations to express CMJ and SJ difference have been suggested in the literature. In addition to EUR, authors have suggested calculations of reactive strength (CMJ-SJ) and the percent pre-stretch augmentation ((CMJ-SJ)/SJ) $\times$ 100) [35], although very similar information is provided in all cases.

Traditionally, it was believed that the difference between SJ and CMJ is largely determined by the capability to store the elastic energy during the braking phase of the CMJ and use it during the propulsive phase. Thus, higher values were though to reflect better efficiency in elastic energy storage [36]. However, later studies have shown that higher forces are developed in CMJ compared to SJ due to the active eccentric portion of the jump prior to the propulsive phase, which enables greater overall power output in CMJ [37,38]. In addition to difference in kinematics between CMJ and SJ (e.g., different lean of the trunk), squat depth is difficult to control accurately, with athletes commonly performing a greater squat depth during the CMJ, which provides additional time for the production of force, resulting in a greater impulse and greater duration for acceleration. Based on that, higher EUR is explained by the better ability to develop high forces in downward phase of the CMJ. It has been suggested that larger EUR can be a consequence of superior CMJ performance, but also lower SJ performance, which could be related to the poor ability to develop force rapidly [37,39] and high levels of muscle slack [40]. Indeed, novel studies show that high values of EUR may not be beneficial at all [33,41].

Since a lower rate of force development and higher muscle slack are associated with poorer jumping performance [40], EUR might not be a valid indicator of performance. It has been reported that EUR was larger in track and field athletes compared to gymnasts and parkour practitioners, while the opposite was observed for jumping ability (SJ and CMJ) [42]. Moreover, a recent study conducted on a large sample of different groups of athletes (nine groups, n = 770) reported that the physical education students exhibited the highest EUR, while track and field athletes, who showed the best overall jumping ability, exhibited the lowest EURs among the tested groups [41]. Similar results are also reported in interventional studies [43,44]. Furthermore, Gehri et al. [43] reported increased jumping ability with no statistically significant changes in EUR after 12 weeks of plyometric training. Similar findings are also reported by Hawkins et al. [44] after weightlifting and plyometric training. On the other hand, Mcguigan et al. [34] reported that EUR could be sensitive to training, although they did not investigate the direct relationship with athletic performance. One of our recent studies found that the correlations between EUR and performance measures were smaller (r = 0.31–0.34) than correlations with SJ and CMJ variables alone (r = 0.33–0.70) [45].

The evidence suggests limited utility of the EUR in sport settings. Based on the literature, EUR should not be interpreted as good or bad in isolation. The relevance of EUR should be determined in the context of the specific sport; thus, general recommendations for training decisions cannot be given based on the value of the EUR. For a better understanding of the usefulness of this variable, future interventional training studies should monitor

EUR and possibly include baseline EUR as a covariate in the analysis to reveal if there is any utility in this metric at all. From a practical standpoint, the current evidence implies that coaches should probably not use EUR for decision making regarding training design. Moreover, it should be noted that the reliability of EUR is lower compared to isolated SJ and CMJ metrics [46], at least in untrained participants.

3. Reactive Strength Index

Reactive strength is the ability to rapidly and efficiently perform an eccentric–concentric muscle contraction within a stretch shortening cycle (SSC) movement [47]. The SSC is present during many sporting activities (i.e., sprinting, jumping, etc.) [48] that depend to a great extent on the ability to develop maximal force in a minimal bout of time [49]. Previous research has defined a variable called RSI, that is a very convenient approach to assess the reactive strength ability [50]. The RSI is obtained from the drop jump (DJ) and presents a measure of produced force and the time to develop this force, which is calculated as the ratio between DJ height and ground contact time [50,51]. Based on the literature, the RSI values of young athletes are around $1.1–1.5 \pm 0.5$ [51,52]. Moreover, recent studies also implied a modified version of RSI (RSI_{mod}), which is obtained from CMJ metrics, and may provide an alternative method for assessing RSI during several different plyometric exercises [53]. In the RSI_{mod} calculation, ground contact time from DJ is replaced with the time to takeoff in CMJ. The values of RSI_{mod} are typically lower than RSI values, ranging from around 0.28 to 0.41 ± 0.08 m/s in collegiate athletes [54].

The rationale for different RSI metrics is that they may specifically target different types of SSC. In brief, SSC is divided into two different types, fast SSC (contact time < 250 ms) [55] and slow SSC, wherein the times of descent and transition to ascent are much longer [56]. DJ is performed with the use of fast SSC, while slow SSC is present in exercises such as CMJ [51]. However, it should also be mentioned that there are some additional differences in jump characteristics between DJ and CMJ. In DJ, ankle strength and stiffness are the main determinants of performance [57], whereas a higher contribution of the knee joints is typical for CMJ [58]. Similar to RSI [59], the RSI_{mod} is considered a reliable measure and was reported to discriminate between different groups of athletes [54,60].

A recent systematic review with meta-analysis showed moderate associations between RSI and physical performance (isomeric strength, isotonic strength, and endurance performance) and moderate to large associations with performance measures (CoD, linear sprint, acceleration ability, top speed ability) [61]. Furthermore, a recent study conducted on university team sport athletes reported that subjects with greater RSI from DJ demonstrated superior horizontal deceleration ability [62], which could be meaningful information for improving CoD ability. However, more studies are needed to confirm this hypothesis. Brumitt et al. [63] also reported the RSI could present an important component for preseason screening for female volleyball athletes. Namely, they found that the players with lower values of RSI (<0.91; 30.5 cm box) were four times more likely to be injured, while this was not true for male basketball players.

A modality commonly used to enhance SSC capabilities is plyometric training. The key characteristics of plyometric training are quick, powerful movements using a pre-stretch or countermovement that involves SSC [64]. The literature reports that RSI may be a potentially useful tool for designing individually tailored plyometric training [51,52]. To prescribe plyometric training, the optimal drop height for DJs is suggested to be based on the highest RSI values [65]. The study by Ramirez-Campillo et al. [52] confirmed this hypothesis on sample of young football players. In the study, the group of athletes who performed DJ training using the heights that were associated with the largest RSI exhibited greater performance benefits than the group of athletes performing DJs at the fixed height. Additionally, studies suggest that RSI_{mod} in bilateral CMJ can be used as a measure of explosiveness in volleyball players [66] and could be used to determine the need of incorporating ballistic-type exercises (i.e., plyometric exercises, weightlifting movements) into an athlete's training program [60]. Moreover, a study on collegiate basketball players

reported that measuring RSI before and after the last practice before the game day can predict speed performance during the basketball match [67]. Authors reported that the athletes with greater post-practice increases in RSI achieved greater peak speeds in a basketball match the following day. Based on those results, exposing the basketball athletes to stimuli that promote the production of maximal force outputs in reduced contact times may be an important part of physical preparation close to competition. Based on the reviewed literature, RSI could be a useful method for preseason testing to detect female athletes with higher injury risk and for in-season testing to measure explosiveness and readiness for the match.

Based on the literature, RSI may be a potentially useful tool for designing individually tailored plyometric training, with the recommendation being to perform DJ from the height associated with the highest RSI values. It can be suggested that plyometric training is performed twice a week for 7 weeks, with the final (seventh) week being a tapering week, as suggested by Ramirez-Campillo et al. [52]. For the new training cycle, the optimal drop height should be re-tested. Furthermore, when planning the training process, we should not forget about the principle of progression. For example, in the aforementioned study, football players progressed from 48 jumps during each session in the first week to 90 jumps per session in the sixth week, with a taper during the seventh week (i.e., same volume as in the first week). This could present a basic scheme for planning plyometric training, from which the training process can be further proceeded and adjusted to the needs of a specific sport or athlete.

4. Bilateral Deficit

The term BLD describes the observation that the muscle force produced during maximal bilateral actions is lower than the sum of forces of the left and right limb generated during unilateral contractions [68,69]. BLD is presented as a negative value of bilateral index (BI), while positive values of BI are termed bilateral facilitation (BLF). In this case, the force produced in the bilateral contractions is greater than the sum of forces during unilateral contractions [68]. There is great variability in the literature regarding the value of BI, with several underlying factors suggested (e.g., movement type, body segments involved, muscle contraction type, participants' characteristics) [69]. It appears that BLD is a more consistent phenomenon in dynamic contractions, with the magnitude being greater in lower body movements compared to upper body movements. Available evidence also suggests that the magnitude of BLD increases with the velocity of contraction [69]. Regarding dynamic contractions, the average BI reported in the review by Škarabot et al. [69] is $-11.7 \pm 9.7\%$, while the average value of BI in isometric contractions is -8.6 ± 8.5. On the other hand, the magnitude of BI in explosive/ballistic contractions can be as high as -36% [70].

The mechanisms of BLD are not fully known yet. In general, studies are reporting on psychological, physiological, and neurological mechanisms. In single-joint movements, BLD is mainly of neurological origin [71], while in more complex, dynamic movement tasks, such vertical jumps, the lower mechanical output produced by the legs in bilateral jumps compared to unilateral jumps is not necessarily a result of reduced neuromuscular activity alone [72]. In bilateral jumps, the power output of the individual leg is lower than the power output in the unilateral movement task [72]. For example, in bilateral CMJ, muscles that extend the legs achieve higher rates of muscle contraction compared to unilateral CMJ, which means that due to the force–velocity relationship, they produce less force and less mechanical work [73]. Moreover, it should be also noted that performance of single leg jump could be affected by poor neuromuscular capabilities associated with a lack of muscle coordination and balance to jump strictly in the vertical direction, thus affecting bilateral index. In addition, muscle activity is lower in the initial position when performing a bilateral jump compared to a unilateral jump, which is due to the distribution of the body weight between two limbs [37,69]. As a result, lower limb muscles are less active in the initial part of the bilateral jump compared to the unilateral jump [69]. Muscle contractions

are faster when performing bilateral movement tasks compared to unilateral ones, because in bilateral tasks, more force can be produced at the same relative load [72]. This suggests that the FV relationship is an important determinant of BLD. Indeed, it has been shown that the more an individual's FV profile favors velocity (i.e., velocity dominance of the profile), the smaller the loss of the force from unilateral to bilateral movement tasks due to the changes in movement velocity [70]. Furthermore, the simulations by Bobbert et al. [72] suggest that 75% of the BLD in the CMJ could be explained as consequence of faster muscle contractions in bilateral jumps compared to unilateral jumps. Theoretically, this could mean that BLD can be reduced or increased by training directed to the velocity capabilities in specific movement tasks, which would reflect a greater ability to produce force at a given velocity and thus greater performance in selected movement task (e.g., higher jump). Nevertheless, more studies are required to confirm this hypothesis. Moreover, previous studies have demonstrated that resistance training emphasizing bilateral actions decreases the BLD, while the training involving unilateral exercises increases it [74–76], which could be important information for guiding training-related decision making, such as preferential inclusion of bilateral or unilateral exercises into athletes' training programs.

To the best of our knowledge, only five studies regarding the associations between BLD and sport performance have been conducted [73,77–80]. The first study by Bračič et al. [73] found that BLD in CMJ was moderately related to peak forces recorded at the rear leg during sprint start and higher total force impulse in elite male sprinters. Based on the reported results, sprinters with higher BLD produced lower rear leg forces and lower total force impulse, suggesting that BLD should be minimized for the optimization of sprint start. However, this study did not report any measures of performance, such as sprint times. Furthermore, Bishop et al. [78] reported that higher BLD could be beneficial for CoD performance. The study reported that higher BLD calculated from CMJ height, CMJ concentric impulse, and drop jump flight time is moderately related to superior performance in 505 CoD tests, as well as smaller CoD deficit. On the other hand, they did not find any associations between sprinting performance and BLD. Similar findings were published a year later in a study on basketball and tennis players, but the reported associations were relatively weak [79]. Inconsistent with reported studies, Ascenzi et al. [77] found no relationship between BLD in CMJ and linear sprint performance or CoD performance in male soccer players. The most recent study on the topic reported no associations between CoD performance and BLD in isokinetic knee extension, and no associations between CoD performance and BLD in SJ variables [80]. Nevertheless, we should be careful about generalizing those results because of the methodological issues related to small sample sizes and, consequently, low statistical power [73,78,80]. Two of the five studies discussed above were also not conducted on athletes [78,80]. Based on the current evidence, BLD seems to be positively associated with CoD ability, but not with sprinting performance. Although the CoD is a complex movement task that requires good movement coordination, those findings suggests that BLD from CMJ could present an interesting method to better understand the missing link for improving CoD performance.

An interesting argument was pointed out by Škarabot et al. [69], that the BLD should not be necessarily viewed as deficit, but rather as "unilateral facilitation", which can be manipulated by the choice of training type (i.e., unilateral or bilateral type of exercises) [74,75]. Although BLD is associated with some specific movement tasks, it should be interpreted with caution for sport diagnostic purposes. Previous studies have demonstrated that resistance training emphasizing bilateral actions decreases the BLD, while the training involving unilateral exercises increases it. If the bilateral facilitation is noted, it is recommended for team sport athletes to incorporate unilateral exercises into their training regime [81] (unless bilateral performance is of primary importance, as in ski jumping). During unilateral training, we can produce greater force per leg, which also reflects in faster morphological changes [71,82]. This could be important information for strength and condition coaches in team sports, because they usually do not have sufficient time available for physical preparation; thus, any method that positively affects this aspect would be worth consideration.

Nonetheless, more studies are needed to further clarify the relevance of BLD for sport performance and thus to help coaches reliably make training-related decisions based on the BLD metrics.

5. Force–Velocity Relationship

FV profiling has recently been proposed as a tool to identify the neuromuscular capabilities of athletes and to optimize their training [83]. FV profiling allows the identification of the mechanical capabilities of the musculoskeletal system to produce force, power, and velocity [84]. Since the early studies on this topic [85], it has been known that the FV relationship in single-joint movements is approximately hyperbolic, while novel studies have shown that the FV relationship in multi-joint tasks is quasi-linear [84,86]. This linear relationship enables us to use linear equations to calculate maximal theoretical force (i.e., the F-intercept; F_0), maximal theoretical velocity (V-intercept; V_0), and maximal power ($P_{max} = F_0 V_0/4$) [84]. The x- and y-axis intercepts (F_0 and V_0) determine the slope of the FV relationship, displaying the individual ratio between force and velocity qualities. Athletes with steeper FV profiles are better at generating high forces at low velocities, and vice versa [87]. Due to its simplicity and cost effectiveness, FV profiling is often applied for different movement tasks, such the vertical jump [87], sprint running [88], and bench press [89]. Nevertheless, it is also important to note that the values of the FV relationship parameters (F_0, V_0, and P_{max}) depend on the movement task.

Vertical jump and bench press FV profiles are usually evaluated through performing the selected movement with systematic increment of loads. Regarding the jumping FV relationship, studies on a sample of athletes from different sports report great variability regarding the values of F_0 (29–40 N/kg), V_0 (2.2–4.3 m/s), and P_{max} (20–30 W/kg) [83,90]. There is also great variability regarding the FV deficit/dominance. While the aforementioned studies report a 45–137% imbalance of the optimal FV profile, studies on football and volleyball players report velocity-dominant profiles (FV imbalance = 33–65%) [91,92].

On the other hand, sprinting FV can be evaluated with a 30 m sprint with split times being recorded every 5 m. Although longer distances are needed to reach top speeds in elite athletes, the 0–30 range is sufficient to extrapolate maximal force (F_0) and velocity (V_0) capabilities. In addition to F_0, V_0, P_{max}, and the slope of the FV relationship, FV profiling in sprinting allows the evaluation of the ability to produce force in the horizontal direction in the acceleration phase [88] and sprinting mechanical efficiency (i.e., maximal ratio of horizontal-to-resultant force, RF) [93]. Similar to the jumping FV relationship, there is also great variability in the values of sprinting FV parameters (regarding the gender and different sports). Haugen et al. [94] reported that F_0 is approximately 9% higher in men (7–10 N/kg) than in women (6–9 N/kg) athletes, while F_0 in elite sprinters is around 11 N/kg [95]. Similar differences between men (7.5–11.0 m/s) and women (6.0–9.5 m/s) are also reported for the V_0 [94], while elite sprinters achieve values as high as 12 m/s [95]. Higher differences between sexes are reported for the P_{max} (men: 13–25 W/kg vs. women: 11–21 W/kg), with similar differences between gender also in elite sprinters (men: 30.3 ± 2.5 W/kg vs. women: 24.5 ± 4.2 W/kg) [95]. Regarding the sprint-specific parameters, RF_{max} is reported to be around 37–48% in women and 41–52% in men, with values up to 57% in elite sprinters. DRF in men and women is similar (7–11%), while elite sprinters achieve values of DRF around 6.4% [96].

The literature suggests that the FV profile can provide meaningful data to implement individualized training programs [27,83]. Interventional studies show that exercises implementing high loads improve athletes' ability to produce force and increase F_0, while training in high-velocity conditions (i.e., plyometric training) increases the V_0 [97]. Thus, different types of training can be used to change the slope of the FV profile. Studies show that by changing the slope of the FV relationship, we can improve the jumping performance independently of the changes in maximal power capabilities [83,98]. On the other hand, a recent interventional study from Lindberg et al. [90] showed no improvements in sport performance in team sport athletes with training based on individual FV characteristics.

Training toward an optimal SJ FV profile did not show favorable effects in SJ height, CMJ height, 10 and 30 m sprint time, 1RM strength, or leg-press power compared to participants either training away from their optimal profile or balanced training irrespective of their initial FV profile. On the other hand, increasing P_{max} in the SJ was positively associated with increases in jumping height, but not with the sprinting performance. However, this study reported just the basic metrics of physical performance but not any measures of sport-specific performance. In terms of sprinting, there is no universal "optimal" FV profile. Rather, there are optimal FV profiles for each combination of a given P_{max} and a given distance [99]. Athletes who wish to maximize short-distance sprint performance (5–10 m) should aim for a force-dominant FV profile, whereas athletes interested in longer sprint performance should strive to achieve a more velocity-dominant profile. Interested readers are referred to a recent work by Samozino et al. [99], wherein the values for optimal sprint FV profile are given across different combinations of P_{max} and distance.

Furthermore, some studies focus on the association between the FV relationship and athletic performance. A study on volleyball players reported strong correlations between F_0 in jumping FV, V_0 in sprinting FV, and moderate correlations between F_0 in bench press FV and P_{max} in all three movements with ball speed in the volleyball spike and serve [89]. Moreover, it has been reported that the CoD ability is related to F_0 and P_{max} of the sprinting FV profile, while the parameters of the FV relationship in the vertical jump showed only few small correlations with CoD [29]. One of our studies reported that approach jump performance was influenced by P_{max} (r = 0.53) and F_0 (r = 0.51) in sprinting, as well as F_0 in jumping (r = 0.45). On the other hand, only the FV variables obtained from sprinting alone contributed to explaining linear sprinting and CoD ability (r = 0.35–0.93) [100]. Marcote-Pequeño et al. [92] reported that jump height was strongly correlated with P_{max} and moderately with V_0 in both jumping and sprinting FV profiles in elite female football athletes, while moderate correlations with F_0 were found only in the sprinting FV profile. On the other hand, 20 m sprint performance was strongly correlated with F_0, V_0, and P_{max} in sprinting FV profile and moderately with P_{max} and V_0 in jumping FV profile. In terms of correlations of FV profiles across tasks, this study reported high correlations between P_{max} in sprinting and P_{max} in jumping, and moderate correlations between V_0 in sprinting and V_0 in jumping. These results suggest that P_{max} could present a general measure of lower limb capacity, while F_0 and V_0 are more specific to the movement task. Based on the reviewed literature, the relevance of the proposed use of FV profiles to guide training regimens in athletes is promising, although it has also been questioned by recent reports [90]. It could be suggested that in general, training should prioritize power ability, while reducing a theoretical FV imbalance could be used as a supplementary part of the training for improving basic physical performance. In other words, it seems to be important to work on shifting the entire FV curve to the right and improving power across the entire FV continuum, while correcting theoretical FV imbalance should be a secondary goal. Furthermore, it seems to make sense to test the FV profile in basic movements (i.e., jump, sprint, and bench press) and check associations with sport-specific performance (e.g., spike or serve speed) to gain a deeper insight into the biomechanical characteristics of a specific movement with the intention to help guide training-related decisions regarding the improvement of sport-specific performance.

6. Conclusions and Practical Applications

A summary of the findings of this review is included in Table 1. Except the EUR, all the above-described variables (to some extent) have potential for evaluating sport performance. When obtaining these selected variables, we systematically change some of the movement components (load in FV relationship; inclusion of eccentric part in EUR; unilateral performance compared to bilateral performance in BLD; drop height in RSI) to gain a deeper insight into an individual's neuromuscular performance. Although these "alternative" variables are more complex in biomechanical terms, they are mostly relatively simple to perform, with no need for additional technology beyond what is already necessary

for performing the conventional tests. Furthermore, the literature reports that even more affordable devices such as contact mats and phone apps (e.g., MyJump 2) are valid and reliable tools for assessing jump height [101] and thus for evaluating BLD and FV profile in jumping, and even for measuring the RSI [102].

Based on this review, the evidence suggests limited utility of the EUR in sport settings. Future interventional training studies should monitor EUR to reveal if there is any utility in this metric at all. From a practical standpoint, the current knowledge implies that EUR does not represent a useful metric for decision making regarding training design. Older literature has established EUR as an indicator of the ability to store and reuse elastic energy, but subsequent research has shown that the difference between SJ and CMJ is mainly due to active state development in the eccentric phase of the CMJ, which enables athletes to execute the jump with higher average force throughout the propulsive phase.

RSI could be a useful method for preseason testing to detect female athletes with higher injury risk (threshold: RSI < 0.91; 30.5 cm box) [63] and for in-season testing to measure explosiveness and readiness for the match (high difference between pre- and post-practice in RSI values is desired for better physical performance on game day). Moreover, the RSI is a useful tool for designing individually tailored plyometric training. Furthermore, the principle of progression should be respected in the training process. A six-week progressive cycle could be suggested, with the following week being a tapering or de-load week. For the new training cycle, the optimal drop height should be re-tested. This scheme of planning plyometric training could be adopted and adjusted to the needs of a specific sport or athlete.

Based on the currently available studies, BLD could be associated with CoD ability, but not with sprinting performance. Moreover, previous studies have demonstrated that resistance training emphasizing bilateral actions decreases BLD, while training involving unilateral exercises increases it, which means that BLD could be manipulated by the choice of training type. Furthermore, if bilateral facilitation or low levels of BLD are observed, it could be suggested to incorporate unilateral exercises into training regime, especially for team sport athletes performing several CoD actions. Nonetheless, more studies are needed to further clarify the relevance of BLD for sport performance and thus to help coaches reliably make training-related decisions based on BLD metrics.

Regarding the FV relationship, the results indicate that P_{max} could present a general measure of lower limb capacity, while F_0 and V_0 are more specific to the movement task. This means that P_{max} can be evaluated in any movement task to gain insight into an individual's capability to produce power, while F_0 and V_0 should be tested in a movement that is associated with sport-specific movement tasks to obtain information about further training adjustments regarding FV imbalance. Moreover, knowing the associations between the FV profile in basic movements (i.e., jump, sprint, and bench press) and sport-specific performance could be useful to guide training-related decisions regarding the improvement of sport-specific performance. Parameters of the FV relationship could be improved by implementing specific exercises into the training design. For example, high-loads are recommended for increasing F_0, while for increasing V_0, training should be performed in high-velocity conditions (i.e., plyometric training). Nevertheless, based on the results of a recent interventional study, it could be suggested that in general, training should prioritize power ability, while reducing a theoretical FV imbalance could be used as a supplementary part of the training for improving basic physical performance.

Although some of the variables were reported as useful tools to guide training-related decision making for improving athlete performance, the basic training principles should not be missed. In this context, one of the key training principles is movement specificity, which suggests that the best performance indicator should be the task that best resembles the demands of the sport-specific movements. One of the important components of the principle of specificity is the force vector theory, which describes that the direction of the resistance force vector relative to the body plays a role in transference to sport-specific performance [103,104]. Furthermore, we should always consider the basic characteristics of the main sport-specific movements from the perspective of the muscle contraction type,

velocity of the movement, and body segments involved. Moreover, it must be stressed that despite the indicated usefulness of described biomechanical variables for deeper insight into athletes' neuromuscular function, such measurements require more time and expertise, and must be performed by qualified practitioners. Furthermore, traditional "first level" tests (jumps, sprints, RM tests, CoD tests) could be less affected by accuracy than presented "second level" tests when the mathematical calculation includes an exponent formula. In addition, practitioners need to be aware that for each presented variable, different protocols and different measurement devices exist, and thus, validity may not be the same for all combinations. The gold standard to evaluate force–time curves are force plates [14–16] and thus are the most reliable method to evaluate the selected biomechanical variables (EUR, RSI, BLD, FVP). Therefore, it is suggested that before using one of the presented variables for sport diagnostic purposes, protocol and measurement devices should be carefully selected.

This review revealed some new opportunities for future research to learn more about presented in-depth macroscopic behavior level testing for sport performance and training optimization. While most of the reviewed tools (apart from EUR) are to some extent presented as potentially useful tools for guiding training-related decisions, more interventional studies are needed to know more about their usefulness in certain training circumstances. Moreover, it would be interesting to analyze the relationship (and changes in time) between different biomechanical variables and sport-specific performance over a longer period of time (for example, the whole season). Fitness testing often occurs at multiple time points throughout a year for team sport athletes (pre-, mid-, and post-season are common), which could provide an opportunity for future studies. Finally, the variables in the review covered only a limited aspect of performance. Other performance variables, particularly sport-specific variables, should be also studied to know more about the usefulness of those tools for analyzing sport-specific performance. An interesting perspective and opportunity for future research would be also to study how additional cognitive tasks (e.g., distractions or decision making) that simulate game situations influence neuromuscular performance, and along with that, if the combination of these tests (neuromuscular performance with cognitive component) correlates with sport performance.

Table 1. Summary of the review findings.

Variable	Calculation	Typical Values	Equipment	Practical Application
EUR	CMJ/SJ	1.05–1.15	Force plate, jump mat, smart phone app, optical sensor (optojump), inertial measurement unit (IMU)	EUR is probably not suitable to be interpreted as good or bad in isolation. The relevance of EUR should be determined in the context of the specific sport. Thus, general recommendations for training decisions cannot be given based on the value of the EUR.
RSI	RSI = Jump height/contact time RSI_{mod} = Jump height/time to take off	RSI = 1.0–2.5 RSI_{mod} = 0.25–0.60	Force plate, jump mat, smart phone app, optical sensor (optojump), inertial measurement unit (IMU)	RSI could be a useful method for preseason testing to detect female athletes with higher injury risk and for in-season testing to measure explosiveness and readiness for the match. RSI is a useful tool for designing individually tailored plyometric training, with the recommendation being to perform DJ from the height associated with the highest RSI values.
BLD	(Bilateral/(right + left unilateral) * 100))–100	Dynamic contractions: −11.7–9.7% Ballistic contractions: up to −36% Isometric contractions: −8.6–8.5	Force plate, jump mat, smart phone app, optical sensor (optojump), inertial measurement unit (IMU)	BLD could be associated with CoD ability. Moreover, BLD can be manipulated with resistance training. Emphasizing bilateral actions decreases the BLD, and emphasizing unilateral exercises increases it. If the bilateral facilitation or low levels of BLD are observed, it could be suggested to incorporate more unilateral exercises into the training regime (unless bilateral performance is of primary importance, as in ski jumping), especially for team sport athletes performing several CoD actions.
FVP jump	Linear regression, using force and velocity data from individual loads to obtain F_0, V_0, and FV slope. Excel spreadsheet available from Samozino's group. $P_{max} = F_0\ V_0/4$	F_0 = 29–40 N/kg V_0 = 2.2–4.3 m/s P_{max} =20–30 W/kg	Force plate, jump mat, velocity tracker, smart phone app, optical sensor (optojump), linear encoder, inertial measurement unit (IMU) Mandatory equipment: weights, measurement tape	P_{max} presents a general measure of lower limb capacity, while F_0 and V_0 are more specific to the movement task. It could be suggested that in general, training should prioritize power ability, while reducing a theoretical FV imbalance could be used as a supplementary part of the training for improving basic physical performance. Parameters of the FV relationship can be improved by implementing specific exercises into training design, such as high loads for increasing F_0, and training in high-velocity conditions (i.e., plyometric training) for increasing V_0.
FVP sprint	Linear regression, using force and velocity data from individual steps to obtain F_0, V_0, and FV slope. Excel spreadsheet available from Samozino's group. P_{max} = F0 V0/4	F_0 = 6–10 N/kg V_0 = 6–11 m/s P_{max} = 11–25 W/kg RF_{max} = 37–53% DRF = 7–11%	Timing gates, smart phone app, gun radar, lidar, linear encoder	Similar to the FVP in jumps, P_{max} is a general measure of lower limb capacity, while F_0 and V_0 are more specific to the movement task. RF_{max} and DRF are specific metrics for evaluating sprinting efficiency. Training towards specific FVP characteristics for improving sport performance should be based on the characteristics of a selected movement task (e.g., improving volleyball spike speed or approach jump performance). Thus, knowing the associations between the FV profile in basic movements (i.e., jump, sprint, and bench press) and sport-specific performance could be useful to guide training-related decisions regarding the improvement of sport-specific performance.

EUR—eccentric utilization ratio; CMJ—countermovement jump; SJ—squat jump; RSI—reactive strength index; RSI_{mod}—modified RSI (from CMJ); BLD—bilateral deficit; FVP—force–velocity profile; F0—maximal theoretical force; V0—maximal theoretical velocity; Pmax—maximal power; RF_{max}—maximal ratio of horizontal-to-resultant force; DRF—decrease in the RF.

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