RELATIONSHIP BETWEEN UNILATERAL AND BILATERAL COUNTERMOVEMENT JUMP PERFORMANCE AND FORCE-VELOCITY-POWER OUTCOME VARIABLES

Darjan Spudić[1] and Ažbe Ribič[1]

[1]*University of Ljubljana, Faculty of Sport, Ljubljana, Slovenia*

Original scientific paper
DOI 10.26582/k.55.2.6

Abstract:

The main objective of the present study was to check the relationship between commonly used unilateral and bilateral countermovement jump (CMJ) performance variables (jump heights, unilateral CMJ jump/bilateral CMJ jump height index, reactive strength index modified and bilateral deficit) and Force-velocity-Power (*F-v-P*) outcomes from loaded CMJs. Seventeen physical education students performed unilateral CMJ jumps, bilateral CMJ jumps and two-load (20 and 70% of the participant's body mass) *F-v-P* tests. The results show that bilateral CMJ jump, unilateral CMJ jump height and the reactive strength index modified calculated from the bilateral CMJ jump are moderately correlated (r = 0.567-0.633, p<.05) to F_0. No statistically significant correlations were found between *F-v-P* outcomes and unilateral CMJ jump height to bilateral CMJ jump index, reactive strength index modified calculated from the unilateral CMJ jump and bilateral deficit. Multiple linear stepwise regressions between *F-v-P* outcomes and performance variables revealed that only F_0 can be statistically significantly predicted by CMJ height (R^2 = 40 %). Although the unilateral and bilateral CMJ tests are less time-consuming and less fatiguing than the progressive loaded CMJ jump test, the results of our study show that the mechanical properties of the lower extremities obtained by unilateral CMJ jump and bilateral CMJ jump cannot be generalized to those measured by *F-v-P* profiling.

Key words: *unilateral, F-v-P profiling, strength, power, ballistic*

Introduction

Ballistic activities (e.g., jumping or sprinting) are closely related to performance in sports such as volleyball, basketball, football, and rugby. Jumping performance is determined by the net force impulse one can directly produce onto the ground (Linthorne, 2001). The capability to produce a high net impulse has been associated with muscular mechanical power output capabilities (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017). It was found that jump height is determined by maximal power output and the lower limb's Force-velocity-Power (*F-v-P*) profile (Samozino, et al., 2014a). The *F-v-P* profile has been proposed as a testing procedure to comprehensively evaluate neuromuscular capabilities. The most common way to determine the individual *F-v-P* profile is by performing vertical jumps under several loading conditions (between five and nine). However, it was recently proposed that the two-point method is a reliable and valid procedure to determine the individual *F-v-P* profile from a vertical jump (García-Ramos, Pérez-Castilla, & Jaric, 2021). A linear regression model is typically applied to the recorded force and velocity data to determine the *F-v-P* profile outcome variables (García-Ramos, et al., 2021), namely maximal theoretical force (F_0), maximal unloaded velocity (v_0) and maximal theoretical power (P_{max}) (Morin & Samozino, 2016; Smajla, Spudić, Kozinc, & Šarabon, 2022). The slope of the *F-v-P* profile (*Slope*) reflects the balance between force and velocity capacities (Samozino, et al., 2012) and it was found that deviation from the optimal *Slope* ($Slope_{opt}$) (Samozino, et al., 2012) limited jumping performance.

Unilateral and bilateral countermovement jumps (CMJ) are commonly utilized tasks to evaluate the ballistic performance of the lower body. Though similar, there is still an evident mechanical and kinematic difference between the two jumps (van Soerst, Roebroeck, Bobbert, Hujing & van Ingen Schenau, 1985). Several studies reported that the amount of force produced per leg in a bilateral countermovement jump (BCMJ) is significantly lower than that of a unilateral countermovement jump (UCMJ) (Bobbert, de Graaf, Jonk, & Casius, 2006). Previous studies also reported a strong correlation (r = 0.72, p<.001) between UCMJ height and concentric peak torque of knee extensors (Alves, et al., 2022; Fischer, et al., 2017). The reasons for lower force produced bilaterally are due to a reduced neural drive (Škarabot, Cronin, Strojnik, & Avela, 2016). When performing a BCMJ, the muscles of the individual legs will be at a reduced state of activation, because the weight is distributed over both legs, meaning that they are further away from their maximal state of activation (Bobbert, et al., 2006). Nonetheless, we can not neglect the non-neural factors, which may influence the lower force in a BCMJ. When comparing the two jumps from a kinematic point of view, we can see that the range of motion (ROM) is greater in BCMJ (van Soerst, et al., 1985). Consequently, some extensor muscles will reach higher shortening velocities. In fact, Bobbert et al. (2006) showed that shortening velocities explained 75% of the deficit in the work per leg. This would mean that, due to the *F-v-P* profile of the lower limbs, these muscles tend to produce less force and less work when performing a BCMJ than when performing a UCMJ.

The literature investigating the relationship between bilateral deficit (BLD) and athletic performance has gained attention in recent years. To date, the BLD, defined by a reduction in the amount of force from a single limb during maximal bilateral actions, has been shown to be weakly to moderately correlated to the approach jump performance, agility, and sprinting performance (Pleša, Kozinc, & Šarabon, 2022a). To the author's knowledge, only one study (Samozino, Rejc, di Prampero, Belli, & Morin, 2014b) has examined the relationship between BLD and *F-v-P* outcome variables, but not $Slope_{opt}$, which has previously been shown to be a predictor of jump performance (Samozino, Rejc, di Prampero, Belli, & Morin, 2012).

Differences in shortening velocities between unilateral and bilateral actions and the displacement of the *F-v-P* curves during bilateral actions have been previously shown (Samozino, et al., 2014b). In comparison to the BCMJ, during the UCMJ, the leg extensor muscles of a single leg react against the whole-body mass, while in the BCMJ conditions, body mass is redistributed between both legs. Therefore, the absolute loading per leg is higher. From a theoretical perspective, UCMJ could represent similar muscle loading conditions as the loaded BCMJ, which indeed requires the application of higher muscle forces at a lower contraction velocity. It likely seems that in UCMJ, muscles work at a higher force-producing capacity, reflecting the force-generating capacities of the muscles. Conversely, during BCMJ, limbs operate at higher velocity, reflecting the velocity and consequently power capacities of the lower limb muscles. The magnitude of BLD or simply an index between UCMJ and BCMJ heights (UCMJ/BCMJ) could potentially be used as a predictor of lower limb *F-v-P* characteristics. The more the *F-v-P* profile is oriented towards force capabilities, the higher the loss of force from unilateral to bilateral push-offs due to changes in movement velocity.

Sports activities (jumping, change of direction) largely depend on the ability to produce maximal force in a minimal bout of time. To quantify such an ability, we can use the reactive strength index (RSI), or in the case of CMJ, reactive strength index modified (RSI_{mod}) (Pleša, Kozinc, Smajla, & Šarabon, 2022b). RSI_{mod} is the ratio between jump height and the time to take off and represents the athlete's reactive strength (Suchomel, Bailey, Sole, Grazer, & Beckham, 2015). Measures of physical and sporting performance are moderately (strength, speed, endurance performance) and largely (change of direction speed) associated with RSI (Jarvis, Turner, Read, & Bishop, 2022). Moreover, McMahon and coworkers (McMahon, Jones, Suchomel, Lake, & Comfort, 2018) revealed that higher RSI_{mod} reflects greater eccentric and concentric force, velocity and power of the CMJ with a similar countermovement displacement and, presumably, the measure could be related to the *F-v-P* characteristics of the lower extremities.

The fact that a higher UCMJ height strongly correlates to the knee extensors' strength (Alves, et al., 2022), guided us to the hypothesis that *F-v-P* outcome variables may be predicted through unilateral and bilateral CMJ performance. We aimed to mimic the concept of the two-point method by utilizing BCMJ and UCMJ force and velocity conditions to map the entire *F-v-P* spectrum. Therefore, the main objective of the present study was to check the relationship between commonly used unilateral and bilateral CMJ performance variables (jump heights, UCMJ/BCMJ height index, RSI and BLD) and *F-v-P* outcomes from loaded CMJs. Understanding the properties associated with the *F-v-P* profiles is important for maximizing jumping performance. Several attempts have been made in the literature to optimize the *F-v-P* assessment protocol and the results of our study aim to answer the question of whether *F-v-P* characteristics can be predicted using only unilateral and bilateral unloaded CMJ test variables.

Materials and methods

Participants

Seventeen active physical education students (ten males: age 23.4±2.2 years, mass 79.2±6.2 kg, height 1.83±0.07 m and seven females, age 22.6±3.5, mass 61.9±4.0 kg, height 1.64±0.05 m), experienced in resistance training, participated in the study. The inclusion criterion was strength-training experience, defined by a training history that included strength exercises at least two times per week in the last five years. They were all experienced in executing vertical jumps (unilateral, bilateral, and loaded jumps), as these jump tests were administered as part of the battery of tests used to assess their physical fitness at least four times a year over the past three to five years. The exclusion criteria were the following: hip and knee injuries (e.g., ligament, meniscus, or cartilage damage), chronic diseases (systemic, cardiac and/or respiratory diseases and neuromuscular disorders), history of lower back pain or other acute injuries in the past six months that could in any way negatively influence maximal jumping performance. We used a Sample size calculator (G*Power ver 3.1, Frank Faul; Universität Kiel, Kiel, Germany) to estimate the sample size needed for the study. We calculated the required number of participants where $\beta = 0.20$, $\alpha = 0.05$ and the hypothesized correlation between the *F-v-P* outcomes and introduced variables (jump heights, UCMJ/BCMJ height index, RSI and BLD) was large ($r = 0.7$) (Samozino, et al., 2014b; Yamauchi, Mishima, Nakayama, & Ishii, 2009). This calculation required 13 participants to be tested. The study was approved by the National Medical Ethics Committee (No. 0120-690/2017/8) and adhered to the tenets of the Oviedo Convention and Declaration of Helsinki. Participants were informed about the testing procedures prior to signing an informed consent. They were instructed to avoid any strenuous exercise at least two days prior to the testing session.

Experimental approach to the problem

The study was designed to compare the variables obtained from unilateral and bilateral CMJ tests to the variables obtained from the two-point *F-v-P* CMJ jump test in a cross-sectional design. Participants attended the laboratory once. Tests were performed in a randomized order to avoid any systematic negative effect of fatigue onto mechanical variables. All tests were performed on a bilateral force plate (model 9260AA6, Kistler, Winthertur, Switzerland) with Kistler MARS software to record ground reaction force data. Testing was preceded by a standard warm-up procedure—a 5-minute ride on a bicycle ergometer at 50 revolutions per minute at about 1.5 W/kg and 5-min of trunk, hips, knees and ankles mobility exercises (10 slow repetitions each). Each participant also performed two to three submaximal introductory CMJs before the testing.

Countermovement jump tests

In the bilateral test execution (Figure 1, A), participants were instructed to stand straight and still in the center of the force plate. In the unilateral test execution (Figure 1, B), participants were instructed to stand straight on one leg in the center of the left or right force plate, respectively. The non-jumping leg was slightly flexed with the foot hovering at the mid-shin level, and no additional swinging of this leg was allowed. The hands were placed on the hips. From this position, participants initiated a fast downward movement until a crouching position with a knee angle of about 90°, followed by a jump for maximal height as quickly and explosively as possible (bilaterally or unilaterally, respectively). The appropriate depth of the countermovement was determined before the testing using a manual goniometer (Saehan Co., Masan, Korea), centered at the lateral epicondyle of the knee and aligned with the lateral malleolus and greater trochanter in the (single-leg) 90-degree squat position. Then, one introductory trial was performed for each jump. One examiner (positioned in a sagittal view) visually verified that the appropriate depth was used during all trials. If the depth was not appropriate, the trial was repeated. For each test, three valid trials were performed with a 1-minute recovery period (Petrigna, et al., 2019). Two minutes of rest were administered between different vertical jump tests. The jump with the maximum achieved height was taken for further analysis.

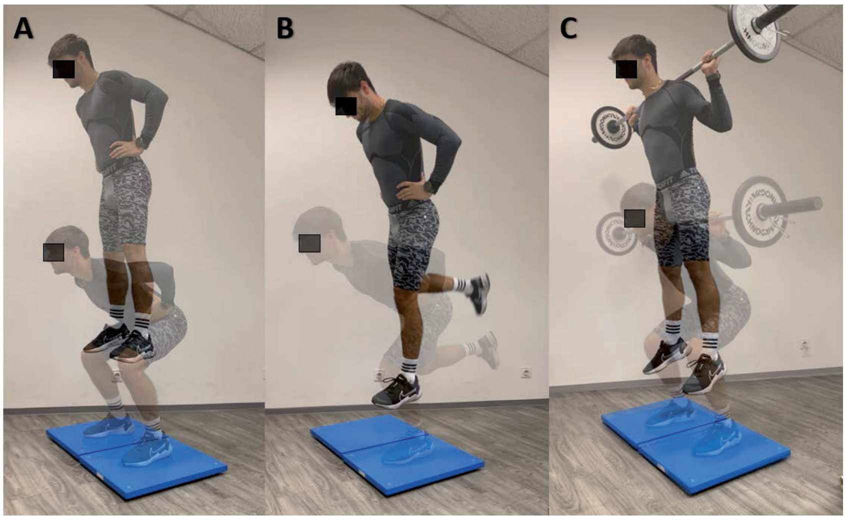

Figure 1. Bilateral (A), unilateral (B) and loaded countermovement jump test execution.

Force-velocity-Power test

A two-point method, introduced by Garcia-Ramos and Jaric (2018), was used to assess the *F-v-P* profile of the lower extremities. Two distant loads were used (García-Ramos, et al., 2021). Bilateral CMJs were performed with the barbell loaded with an additional 20% and 70% of the participant's body mass. Hands were placed onto the barbell and remained in the same position during the jump (Figure 1, C). Leg length (distance from the tip of the big toe with the ankle in plantar flexion to the anterior superior iliac spine), and the height of the initial squat (distance from the ground to the anterior superior iliac spine during a standardized 90-degree squat; position description above) were measured to calculate the push-off distance (Samozino, Morin, Hintzy, & Belli, 2010) (i.e., lower extremities extension range). One introductory trial was performed with each load. As for the unloaded jumps, one of the examiners (positioned in a sagittal view) visually verified that the appropriate depth was used during all trials. If the depth was not appropriate, the trial was repeated. For each loading condition, three valid trials were performed. The rest between the jumps was one minute, and between the two loading conditions there were two minutes of rest. The jump with the maximum achieved height at each loading condition was taken for further analysis.

Data analysis

Ground reaction force data during CMJ were sampled at 1,000 Hz, filtered using a moving average filter with 50-ms window and analyzed using the Kistler MARS software built-in module for CMJ. Recorded metrics included jump time, jump height (calculated using impulse-momentum method), average concentric force and average concentric velocity of the push-off. Based on average force and velocity data in loaded CMJs conditions, the least squared linear regression model was used to determine the four outcome measures of the *F-v-P* relationships, where F_0 represented the force-intercept and *Slope* was the inclination of the force-velocity curve. Additionally, v_0 (maximal theoretical velocity, i.e., x-intercept) and P_{max} $(F_0 \cdot V_0)/4)$ were calculated following the instructions of Samozino et al. (2012). The deviation from the theoretical optimal *Slope* (i.e., inclination of force-velocity curve maximizing vertical jumping performance for given values of P_{max} and push-off distance) was computed in % for each subject as proposed by Samozino et al. (2014a).

Moreover, RSI_{mod} for bilateral and unilateral CMJs were calculated as an index between jump height and jump time (calculated as time from the initiation of the countermovement to the point of takeoff) (Heishman, et al., 2019). Self preferred push-off leg was used in the calculation of unilateral RSI_{mod}. Finally, BLD was calculated from the average net force (GRF – body weight) from the CMJs (Equation 1) as proposed by Škarabot et al. (2016):

$$\mathrm{BLD}(\%) = \left(100 \times \frac{bilateral}{righ+left\ unilateral}\right) - 100 \quad (1).$$

Statistical analysis

All statistical analyses were performed using SPSS software package (version 26.0, Armonk, NY, IBM Corporation). The associations between *F-v-P* outcomes and other variables (jump heights, UCMJ/BCMJ height index, RSI and BLD) were assessed by the Pearson's correlation coefficient and Spearman's Rho coefficient. Multiple linear stepwise regressions (forward selection) were conducted with *F-v-P* outcomes as dependent variables and jump heights, UCMJ/BCMJ height index, RSI and BLD variables as candidate predictors. Before conducting the statistical analyses, several assumptions were checked. The normal distribution of data was assessed using Shapiro-Wilk tests. Linearity and homoscedasticity were examined through scatter plots. The presence of outliers was determined using standardized residuals statistics (values between -3 and 3), normality of residuals with predicted probability plots, and independence of observations with the Durbin-Watson test (values between 1 and 3 were considered acceptable). Durbin-Watson statistics and collinearity diagnostic tests were performed. We conservatively set the thresholds for the presence of collinearity at ≤0.3 for tolerance and ≥3 for variance inflation factor. Correlation coefficients were interpreted according to Hopkins (2000) (0.00–0.19 trivial; 0.20–0.29 small; 0.30–0.49 moderate; 0.50–0.69 large; 0.70–0.89 very large; 0.90–0.99 nearly perfect; 1.00 perfect). The successive predictors were included in the regression model if they statistically significantly ($p<.05$) contributed to the proportion of explained variance in *F-v-P* outcome variables (i.e., probability of F entry: $p \leq .05$, probability of F removal: $p \geq .10$).

Results

Descriptive statistics of the test results is shown in Table 1.

The results of the correlation analyses are shown in Table 2. The results show that CMJ height, UCMJ height and the $RSImod_{BCMJ}$ variables are statistically significantly correlated to F_0 (r = 0.567-0.633, moderate correlation). All other variables (predictors) were not statistically significantly correlated (trivial to moderate magnitudes of correlation) with *F-v-P* outcomes (dependent variables).

Stepwise regression indicated that only BCMJ height was able to predict the F_0 (r = 0.633, R^2 = 40 %, p=.006, equation: F_0 = 48.8 * BCMJ height + 15.2).

Table 1. Descriptive statistics of the obtained variables

Variables	Mean (SD)	95% CI (lower; upper)	Range (min; max)
BCMJ height [m]	0.348 (0.073)	0.311; 0.385	0.226; 0.447
UCMJ height [m]	0.163 (0.038)	0.143; 0.182	0.101; 0.241
UCMJ height/BCMJ height	0.47 (0.04)	0.45; 0.49	0.39; 0.54
$RSImod_{BCMJ}$ [m/s]	0.48 (0.13)	0.42; 0.54	0.30; 0.68
$RSImod_{UCMJ}$ [m/s]	5.27 (1.60)	4.45; 6.10	3.26; 9.49
BLD [%]	-9.9 (10.1)	-15.1; -4.7	-33.2; 11.3
F_0 [N/kg]	32.19 (5.61)	29.30; 35.07	24.02; 44.85
v_0 [m/s]	4.95 (2.10)	3.87; 6.03	3.20; 10.57
P_{max} [W/kg]	37.88 (10.06)	32.71; 43.05	25.73; 63.46
Slope ($N \cdot s \cdot m^{-1} \cdot kg^{-1}$)	-7.57 (3.09)	-9.15; -5.98	-13.49; -2.27
$Slope_{opt}$ [%]	56.9 (23.5)	44.8; 69.0	16.2; 101.5

Note. CI – confidence interval; SD – standard deviation; BCMJ – bilateral countermovement jump; UCMJ – unilateral countermovement jump; RSImod – reactive strength index modified; BLD – bilateral deficit; F_0 – maximal theoretical force, v_0 – maximal theoretical velocity; P_{max} – maximal theoretical power; *Slope* – inclination of the force-velocity regression line; $Slope_{opt}$ – magnitude of the difference between actual and optimal inclinations of force-velocity regression lines.

Table 2. Correlation analysis results

Variables	F_0 [N/kg]	v_0 [m/s]	P_{max} [W/kg]	*Slope* ($N \cdot s \cdot m^{-1} \cdot kg^{-1}$)	$Slope_{opt}$ [%]
BCMJ height [m]	0.633** (0.219; 0.854)	-0.113 (-0.573; 0.402)	0.308 (-0.202; 0.687)	-0.35 (-0.711; 0.157)	0.341 (-0.167; 0.706)
UCMJ height [m]	0.567* (0.119; 0.823)	0.005 (-0.496; 0.489)	0.326 (-0.183; 0.698)	-0.288 (-0.675; 0.224)	0.278 (-0.234; 0.669)
UCMJ height/BCMJ height	0.024 (-0.462; 0.499)	0.020 (-0.507; 0.477)	0.122 (-0.381; 0.569)	0.037 (-0.452; 0.509)	-0.04 (-0.511; 0.449)
$RSImod_{BCMJ}$ [m/s]	0.589* (0.15; 0.833)	0.056 (-0.449; 0.534)	0.403 (-0.096; 0.74)	-0.272 (-0.666; 0.24)	0.26 (-0.252; 0.659)
$RSImod_{UCMJ}$ [m/s]	-0.408 (-0.743; 0.09)	-0.049 (-0.529; 0.454)	-0.479 (-0.78; 0.002)	0.109 (-0.392; 0.561)	-0.099 (-0.553; 0.401)
BLD [%]	0.373 (-0.131; 0.724)	-0.150 (-0.598; 0.370)	-0.03 (-0.504; 0.457)	-0.307 (-0.687; 0.203)	0.305 (-0.206; 0.685)

Note. Pearson correlation coefficients with 95% confidence intervals are represented for all the variables except for v_0, where Spearman's rho was calculated due to non-normal data distribution. BCMJ – bilateral countermovement jump; UCMJ – unilateral countermovement jump; RSImod – reactive strength index modified; BLD – bilateral deficit; F_0 – maximal theoretical force, v_0 – maximal theoretical velocity; P_{max} – maximal theoretical power; *Slope* – inclination of the force-velocity regression line; $Slope_{opt}$ – magnitude of the difference between actual and optimal inclinations of force-velocity regression lines; * – p<.05; ** – p<.001.

Discussion and conclusions

The aim of our study was to analize the relationship between the *F-v-P* profile parameters and UCMJ and BCMJ performance variables. Our results show that CMJ height, UCMJ height and the $RSImod_{BCMJ}$ are moderately correlated (r = 0.567-0.633, p<.05) to F_0. Moreover, only BCMJ height was able to statistically significantly predict the F_0 result (r = 0.633, R^2 = 40 %). Other predictor variables did not show any statistically significant correlation with the *F-v-P* profile parameters. Therefore, the results partly support the main hypothesis that UCMJ and BCMJ variables can be used for predicting the *F-v-P* profile parameters of the lower body while performing ballistic movements. All three variables were moderately correlated to F_0, but not to the other *F-v-P* profile parameters. F_0 reflects the maximum concentric force output that the athlete's lower limbs can theoretically produce during ballistic push-off at null velocity (Morin & Samozino, 2016; Nishioka & Okada, 2022; Samozino, et al., 2012). Therefore, the association between CMJ height, UCMJ height and the $RSImod_{BCMJ}$ and F_0 could mean that these variables are indices that evaluate the ability to produce force at lower velocities. However, although CMJ height, UCMJ height, and the $RSImod_{BCMJ}$ may serve as F_0 indicators, these vertical jump variables have a low impact on F_0. Only BCMJ height was able to predict F_0 result, explaining 40% of the variance.

Through the literature, several studies assessed the association between performance variables and the *F-v-P* profile. A study done by Nishioka and Okada (2022) evaluated the association between drop jump reactive strength index (DJ RSI) and the parameters of *F-v-P* profiles obtained from

SJ and CMJ. Their results showed that DJ RSI was not significantly correlated with any vertical *F-v-P* profile parameter. In contrast, we have found a statistically significant correlation between $RSImod_{BCMJ}$ and F_0. The difference in the results could be due to the RSI parameter that was used. We used $RSImod_{BCMJ}$, where the movement pattern is the same as the *F-v-P* profiling testing procedure. Another reason for the different results could be due to the specificity of the stretch-shortening cycle (SSC) type. DJ is performed with the use of fast SSC, while slow SSC is present while performing a CMJ. Previous studies reported a strong linear association between bilateral squat jump height and P_{max} (r = 0.78-0.84; p<.01), but no association between jump height and F_0 (r = -0.14; p>.01) (Kozinc, Marković, Hadžić, & Šarabon, 2021; Marcote-Pequeño, et al., 2019; Samozino, et al., 2014a). This is in contrast with our findings, where BCMJ height had moderate statistically significant associations with F_0 (r = 0.63) but not with P_{max}. Similar to our study, Kozinc et al. (2021) used a UCMJ to evaluate the association between jump height and *F-v-P* profile. Their results showed that unilateral CMJ height has a moderate to weak but statistically significant correlation with the isokinetic knee extension F_0 (r = 0.48). This agrees with our results, where we found a moderate correlation between UCMJ height and F_0 (r = 0.57). The reason behind the weak correlation between UCMJ variables and *F-v-P* profile parameters could be due to unilateral jumping. An individual has to overcome the same weight and inertia by one leg exclusively, compared to bilateral jumping. This can affect the *F-v-P* relationship by reducing the shortening velocity of leg extensor muscles (Bobbert, et al., 2006; Kozinc, et al., 2021). Moreover, lower shortening velocities in UCMJ muscles mean that a higher force-producing capacity is expressed (Samozino, et al., 2014b). Thus, we can speculate that as bilateral actions rely on the performance of two limbs at the same time, it seems unlikely that both limbs operate at their highest force-producing capacity, which could contribute to bilateral deficit irrespective of physiology.

In our study, we used the two-point method to assess the *F-v-P* profile of the lower extremities. The method has been proven to be valid, but it can be speculated that the reliability of the results is lower than by using multiple (5-7) load method procedure because low reliability of one of the experimental points may highly compromise the accuracy of the 2-point method (Garcia-Ramos & Jaric, 2018) and consequently the results of our study. Moreover, participants were instructed to perform an explosive countermovement jumps (unilateral, bilateral, and loaded) to the 90-degree knee angle position. The results of previous investigations showed that deep countermovements increase net vertical impulse, leading to a higher jump height (Sánchez-Sixto, Harrison, & Floría, 2018). Moreover, it was shown that self-preferred and 90-degree knee angle-loaded squat jumps differ in absolute values and reliability of the *F-v-P* outcomes (Janicijevic, et al., 2020). Especially when unilateral CMJs are performed, the amplitude of the jump is more demanding to standardize. Relatively higher unilateral average ground reaction force (27 %) and higher average velocity (21 %) were produced in UCMJ than in BCMJ, presumably due to a higer absolute loading per individual leg. Moreover, in strength trained athletes, eccentric overload prior to the concentric phase of the front squat enhances the velocity and power of the vertical movement (Munger, et al., 2017). Due to a higher absolute loading in UCMJ, eccentric overload could have been more emphazised and therefore the effect of the potentiation was higher. On the one hand, higher unilateral forces could be a consequence of mechanisms, defining BLD. But on the other hand, neural inhibition could have limited the force produced by the muscles in the unilateral jump test (Aagaard, 2003; Aagaard et al., 2000; Škarabot, Brownstein, Casolo, Del Vecchio, & Ansdell, 2021). It seems that inhibitory mechanisms were not emphasized in our study, because of higer relative forces per leg produced in UCMJ. The reason for that could be highly strength trained individuals included in the study. Postural stabilization requirements during unilateral actions also influence the expression of bilateral deficit to a great extent (Škarabot, et al., 2016). Coactivation, which increases joint stiffness during balance tasks, could have impaired dynamic net force production (Latash, 2018) in the ankle, knee, and hip joints in UCMJ. Moreover, we included 17 participants in the analysis, which is slightly more than the required number based on *a priori* sample size calculation. Nevertheless, the relatively low sample size could have resulted in a low power of correlation statistics, increasing the likelihood of a Type II error. In other words, due to the low sample size and low correlation coefficients in some variables, we cannot confirm our assumption that there is a statistically significant correlation between some *F-v-P* outcomes and unilateral and bilateral CMJ performance variables, even though it may be true.

In conclusion, the commonly used unilateral and bilateral CMJ performance variables (jump heights, UCMJ/BCMJ height index, RSImod, and BLD) are of limited use in predicting *F-v-P* profile parameters. Although the UCMJ and BCMJ tests are less time-consuming and less fatiguing than progressive loaded CMJ test, the results of our study show that the mechanical properties of the lower extremities obtained by UCMJ and BCMJ cannot be generalized to those calculated by the *F-v-P* profiling.

References

Aagaard, P. (2003). Training-induced changes in neural function. *Exercise and Sport Sciences Reviews*, *31*(2), 61-67. https://doi.org/10.1097/00003677-200304000-00002

Aagaard, P., Simonsen, E.B., Andersen, J.L., Magnusson, S.P., Halkjær-Kristensen, J., & Dyhre-Poulsen, P. (2000). Neural inhibition during maximal eccentric and concentric quadriceps contraction: Effects of resistance training. *Journal of Applied Physiology*, *89*(6), 2249-2257. https://doi.org/10.1152/jappl.2000.89.6.2249

Alves, B.M.O., Scoz, R.D., Burigo, R.L., Ferreira, I.C., Ramos, A.P.S., Mendes, J.J.B., …, & Amorim, C. F. (2022). Association between concentric and eccentric isokinetic torque and unilateral countermovement jump variables in professional soccer players. *Journal of Functional Morphology and Kinesiology*, *7*(1). https://doi.org/10.3390/jfmk7010025

Bobbert, M.F., de Graaf, W.W., Jonk, J.N., & Casius, L.J.R. (2006). Explanation of the bilateral deficit in human vertical squat jumping. *Journal of Applied Physiology*, *100*, 493-499. https://doi.org/10.1152/japplphysiol.00637.2005

Fischer, F., Blank, C., Dünnwald, T., Gföller, P., Herbst, E., Hoser, C., & Fink, C. (2017). Isokinetic extension strength is associated with single-leg vertical jump height. *Orthopaedic Journal of Sports Medicine*, *5*(11). https://doi.org/10.1177/2325967117736766

Garcia-Ramos, A., & Jaric, S. (2018). Two-point method: A quick and fatigue-free procedure for assessment of muscle mechanical capacities and the 1 repetition maximum. *Strength and Conditioning Journal*, *40*(2), 54-66. https://doi.org/10.1519/ssc.0000000000000359

García-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2021). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics*, *20*(3), 274-289. https://doi.org/10.1080/14763141.2018.1545044

Heishman, A., Brown, B., Daub, B., Miller, R., Freitas, E., & Bemben, M. (2019). The influence of countermovement jump protocol on reactive strength index modified and flight time: Contraction time in collegiate basketball players. *Sports*, *7*(2), 37. https://doi.org/10.3390/sports7020037

Hopkins, W.G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine*, *30*(5), 375-381. https://doi.org/10.2165/00007256-200030050-00005

Janicijevic, D., Knezevic, O., Mirkov, D., Pérez-Castilla, A., Petrovic, M., Samozino, P., & Garcia-Ramos, A. (2020). Assessment of the force-velocity relationship during vertical jumps: Influence of the starting position, analysis procedures and number of loads. *European Journal of Sport Science*, *20*(5), 614-623. https://doi.org/10.1080/17461391.2019.1645886

Jarvis, P., Turner, A., Read, P., & Bishop, C. (2022). Reactive strength index and its associations with measures of physical and sports performance: A systematic review with meta-analysis. *Sports Medicine*, *52*(2), 301-330. https://doi.org/10.1007/s40279-021-01566-y

Jiménez-Reyes, P., Samozino, P., Brughelli, M., & Morin, J.B. (2017). Effectiveness of an individualized training based on force-velocity profiling during jumping. *Frontiers in Physiology*, *7*, 677. https://doi.org/10.3389/fphys.2016.00677

Kozinc, Ž., Marković, G., Hadžić, V., & Šarabon, N. (2021). Relationship between force-velocity-power profiles and inter-limb asymmetries obtained during unilateral vertical jumping and single-joint isokinetic tasks. *Journal of Sports Sciences*, *39*(3), 248-258. https://doi.org/10.1080/02640414.2020.1816271

Latash, M.L. (2018). Muscle coactivation: Definitions, mechanisms, and functions. *Journal of Neurophysiology*, *120*(1), 88-104. https://doi.org/10.1152/jn.00084.2018

Linthorne, N.P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physiology*, *69*(11), 1198-1204. https://doi.org/10.1119/1.1397460

Marcote-Pequeño, R., García-Ramos, A., Cuadrado-Peñafiel, V., González-Hernández, J.M., Gómez, M.Á., & Jiménez-Reyes, P. (2019). Association between the force–velocity profile and performance variables obtained in jumping and sprinting in elite female soccer players. *International Journal of Sports Physiology and Performance*, *14*(2), 209-215. https://doi.org/10.1123/ijspp.2018-0233

McMahon, J.J., Jones, P.A., Suchomel, T.J., Lake, J., & Comfort, P. (2018). Influence of the reactive strength index modified on force- and power-time curves. *International Journal of Sports Physiology and Performance*, *13*(2), 220-227. https://doi.org/10.1123/ijspp.2017-0056

Munger, C.N., Archer, D.C., Leyva, W.D., Wong, M.A., Coburn, J.W., Costa, P.B., & Brown, L.E. (2017). Acute effects of eccentric overload on concentric front squat performance. *Journal of Strength and Conditioning Research*, *31*(5), 1192-1197. doi: 10.1519/JSC.0000000000001825

Morin, J.B., & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. *International Journal of Sports Physiology and Performance*, *11*, 267-272. https://doi.org/10.1123/ijspp.2015-0638

Nishioka, T., & Okada, J. (2022). Associations of maximum and reactive strength indicators with force-velocity profiles obtained from squat jump and countermovement jump. *PLoS One*, *17*(10), e0276681. https://doi.org/10.1371/journal.pone.0276681

Petrigna, L., Karsten, B., Marcolin, G., Paoli, A., D'Antona, G., Palma, A., & Bianco, A. (2019). A review of countermovement and squat jump testing methods in the context of public health examination in adolescence: Reliability and feasibility of current testing procedures. *Frontiers in Physiology*, *10*, 1384. https://doi.org/10.3389/fphys.2019.01384

Pleša, J., Kozinc, Ž., & Šarabon, N. (2022a). Bilateral deficit in countermovement jump and its influence on linear sprinting, jumping, and change of direction ability in volleyball players. *Frontiers in Physiology*, *13*, 768906. https://doi.org/10.3389/fphys.2022.768906

Pleša, J., Kozinc, Ž., Smajla, D., & Šarabon, N. (2022b). The association between reactive strength index and reactive strength index modified with approach jump performance. *PLoS One*, *17*(2), e0264144. https://doi.org/10.1371/journal.pone.0264144

Samozino, P., Edouard, P., Sangnier, S., Brughelli, M., Gimenez, P., & Morin, J.B. (2014a). Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. *International Journal of Sports Medicine*, *35*(6), 505-510. https://doi.org/10.1055/s-0033-1354382

Samozino, P., Morin, J.B., Hintzy, F.F., & Belli, A. (2010). Jumping ability: A theoretical integrative approach. *Journal of Theoretical Biology*, *264*(1), 11-18. https://doi.org/10.1016/j.jtbi.2010.01.021

Samozino, P., Rejc, E., di Prampero, P.E., Belli, A., & Morin, J.B. (2012). Optimal force-velocity profile in ballistic movements-Altius: Citius or fortius? *Medicine and Science in Sports and Exercise*, *44*(2), 313-322. https://doi.org/10.1249/MSS.0b013e31822d757a

Samozino, P., Rejc, E., di Prampero, P.E., Belli, A., & Morin, J.B. (2014b). Force-velocity properties' contribution to bilateral deficit during ballistic push-off. *Medicine and Science in Sports and Exercise*, *46*(1), 107-114. https://doi.org/10.1249/MSS.0b013e3182a124fb

Sánchez-Sixto, A., Harrison, A.J., & Floría, P. (2018). Larger countermovement increases the jump height of countermovement jump. *Sports*, *6*(4), 1-8. https://doi.org/10.3390/sports6040131

Smajla, D., Spudić, D., Kozinc, Ž., & Šarabon, N. (2022). Differences in force-velocity profiles during countermovement jump and flywheel squats and associations with a different change of direction tests in elite karatekas. *Frontiers in Physiology*, *13*, 828394. https://doi.org/10.3389/fphys.2022.828394

Suchomel, T.J., Bailey, C.A., Sole, C.J., Grazer, J.L., & Beckham, G.K. (2015). Using reactive strength index-modified as an explosive performance measurement tool in Division I athletes. *Journal of Strength and Conditioning Research*, *29*(4), 899-904. https://doi.org/10.1519/JSC.0000000000000743

Škarabot, J., Brownstein, C.G., Casolo, A., Del Vecchio, A., & Ansdell, P. (2021). The knowns and unknowns of neural adaptations to resistance training. *European Journal of Applied Physiology*, *121*(3), 675-685. https://doi.org/10.1007/s00421-020-04567-3

Škarabot, J., Cronin, N., Strojnik, V., & Avela, J. (2016). Bilateral deficit in maximal force production. *European Journal of Applied Physiology*, *116*(11-12), 2057-2084. https://doi.org/10.1007/s00421-016-3458-z

van Soerst, A.J., Roebroeck, M.E., Bobbert, M.F., Huijing, P.A., & van Ingen Schenau, G.J. (1985). A comparison of one-legged and two-legged countermovement jumps. *Medicine and science in sports and exercise*, *17*(6), 635-639. doi: 10.1249/00005768-198512000-00002.

Yamauchi, J., Mishima, C., Nakayama, S., & Ishii, N. (2009). Force-velocity, force-power relationships of bilateral and unilateral leg multi-joint movements in young and elderly women. *Journal of Biomechanics*, *42*(13), 2151-2157. https://doi.org/10.1016/j.jbiomech.2009.05.032

Submitted: November 22, 2022
Accepted: July 13, 2023
Published Online First: November 8, 2023

Correspondence to:
Darjan Spudić, Ph.D.
University of Ljubljana, Faculty of Sport
Gortanova 22, 1000 Ljubljana, Slovenia
Phone: +386 (0)40 866 892
E-mail: darjan.spudic@fsp.uni-lj.si