VERTICAL OR HORIZONTAL FORCE–VELOCITY PROFILE: WHICH ONE IS MORE SENSITIVE TO DETECT THE FATIGUE INDUCED BY A BASKETBALL-SPECIFIC PROTOCOL?

Zhaoqian Li[1], Linna Gao[2], Xing Zhang[1], Kuiying Deng[3], Yaodong Gu[2,4], Danica Janicijevic[2,4], and Amador García-Ramos[1,5]

[1]Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Spain
[2]Faculty of Sports Science, Ningbo University, Ningbo, China
[3]School of Sports Engineering, Beijing Sport University, Beijing, China
[4]Department of Radiology, Ningbo No. 2 Hospital, Ningbo, Chin
[5]Department of Sports Sciences and Physical Conditioning, Faculty of Education, Universidad Católica de la Santísima Concepción, Concepción, Chile

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Abstract:

This study aimed to determine which task (jumping or sprinting) and which force-velocity (F-V) relationship parameter (maximal force [F_0], maximal velocity [v_0], or maximal power [P_{max}]) is the most sensitive indicator of fatigue induced by a basketball-specific protocol. Following a familiarization session, 19 junior male basketball players completed an experimental session in which both vertical (jumping) and horizontal (sprinting) F-V profiles were measured before, during and after undergoing a basketball-specific fatigue protocol (modified version of the Loughborough Intermittent Shuttle Test). All F-V relationship parameters, except horizontal F_0 (p = .328), were significantly reduced after fatigue (p ≤ .042). The vertical P_{max} (ES = -0.48 to -0.80), horizontal P_{max} (ES = -0.58 to -1.28), and horizontal v_0 (ES = -0.81 to -0.98) showed larger reductions compared to the pre-fatigue assessment than the vertical v_0 (ES = -0.19 to -0.27), vertical F_0 (ES = -0.16 to -0.25), and horizontal F_0 (ES = -0.11 to -0.30). When the percentage changes with respect to the pre-fatigue assessment were compared between the jumping and sprinting tasks, no significant differences in their magnitude (p ≥ .364) and trivial to small correlations ($-0.23 \le r \le 0.19$) were detected. The results suggest that P_{max} is the most suitable parameter to detect fatigue following a basketball-specific fatigue protocol, while the lack of significant correlations for the changes in F-V relationship parameters highlight the importance of measuring both the vertical and horizontal F-V profiles to gain comprehensive understanding of the changes in the mechanical properties of lower-body muscles following fatigue protocols.

Keywords: *jump, monitoring, sprint, team sport, testing*

Introduction

Basketball is one of the most popular team sports worldwide and has captivated both players and spectators with its dynamic characteristics (B. Li & Xu, 2021). Time-motion analysis reveals that the majority of actions in basketball are of short duration and high intensity (McInnes, Carlson, Jones, & McKenna, 1995). For example, modern competitive basketball demands that players perform repeated high-intensity actions such as accelerations, decelerations, vertical jumps, and quick changes of direction, which are especially important during key moments like shooting, rebounding, or dribbling (García, Castellano, Reche, & Vázquez-Guerrero, 2021). The use of novel technologies has provided a better understanding of the physical demands in elite basketball, showing that players run an average of approximately 80 meters per minute, with peak speeds exceeding 18 km/h (Puente, Abián-Vicén, Areces, López & Del Coso, 2017). Sprinting and jumping abilities not only influence players' physical fitness but also exhibit a strong association with basketball-specific technical skills (Pliauga, et al., 2015). For instance, enhancing jump ability increases the likelihood of securing rebounds, while increasing speed ensures players can swiftly reach offensive and defensive positions during quick transitions (Asadi, 2016). Another important factor to consider is that the repetition of high-intensity actions in basketball exposes players to fatigue, impairing sports performance and increasing the risk of injury during the game (Scanlan, et al., 2017). Basketball-specific fatigue protocols have been shown to compromise both technical elements performance, such as dribbling and shooting velocity and accuracy (F. Li, Rupčić, & Knjaz, 2021; Lyons, Al-Nakeeb, & Nevill, 2006; Mulazimoglu, Yanar, Evcil, & Duvan, 2017), and physical components, including jumping and sprint performance, as well as landing technique (Liveris, et al., 2021; Pliauga, et al., 2015). Given a significant impact of jumping and sprinting on basketball performance and their susceptibility to fatigue, monitoring their performance holds potential value for basketball players.

The assessment of the force-velocity (F-V) profile in jumping and sprinting tasks has recently seen a surge in popularity among strength and conditioning coaches (Morin & Samozino, 2016). This growing interest can be attributed to two key factors: (i) the comprehensive insights their parameters provide into the maximal capabilities of the neuromuscular system for generating force (F_0), velocity (v_0), and power (P_{max}), and (ii) the straightforward and inexpensive nature of this testing method, which primarily involves measuring kinematic variables such as flight time or displacement-time data (Haugen, Breitschädel, & Samozino, 2020; Z. Li, Zhi, Yuan, García-Ramos, & King, 2024). The insights gained from F-V profile assessments have been utilized to tailor individualized training programs with the dual goals of enhancing ballistic performance and reducing the risk of injury (Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Mendiguchia, et al., 2016). In addition, F-V profiles have been recently used to assess the acute fatigue induced by different physical protocols (García-Ramos, et al., 2018; Z. Li, et al., 2024). Its application is recommended because the same decrement in P_{max}, indicative of overall fatigue originated from the physical protocol, can result from varying decreases in F_0 and v_0 (Hermosilla-Palma, et al., 2023; Jiménez-Reyes, Cross, et al., 2018; Z. Li, et al., 2024). Regarding the sensitivity of horizontal (sprint) F-V profiles to detect fatigue, it has been shown that repeated sprint protocols compromise v_0 more than F_0 (Hermosilla-Palma, et al., 2023; Jiménez-Reyes, Cross, et al., 2018). On the other hand, vertical (jump) F-V profiles were sensitive enough to detect a greater decrement in F_0 compared to v_0 following a heavy-load squat protocol, and a greater impairment in v_0 compared to F_0 after a light-load ballistic squat protocol (Z. Li, et al., 2024). Considering the significant involvement of the lower limbs in basketball, it is important to investigate whether vertical and horizontal F-V profiles can be utilized to monitor the specific fatigue impact of this more comprehensive task on F_0, v_0, and P_{max}.

Research has consistently demonstrated a strong correlation between jump height and sprint time (Köklü, Alemdaroğlu, Özkan, Koz, & Ersöz, 2015; Washif & Kok, 2022). Likewise, Jiménez-Reyes et al. (2019) observed similar decreases in jump height and sprint velocity following a repeated sprint training protocol. This suggests that jumping and sprinting abilities may share common physiological and biomechanical underpinnings (Köklü, et al., 2015). However, Jiménez-Reyes, Samozino, et al. (2018) also found generally weaker correlations for F-V relationship parameters (F_0 and v_0) than for performance variables (jump height and sprint time) in jumping and sprinting tasks. Consequently, it becomes critical to ascertain whether vertical and horizontal F-V profiles are sensitive equally for detecting fatigue caused by a basketball-specific protocol. This area of research is groundbreaking, as no previous research has concurrently investigated sensitivity of both the vertical and horizontal F-V profiles in the context of fatigue monitoring.

To address the questions, we measured the vertical and horizontal F-V profiles at three time points: before (pre), during (mid) and after (post) undergoing a basketball-specific fatigue protocol. The main objective of the present study was to determine which task (jumping or sprinting) and which F-V relationship parameter (F_0, v_0, or P_{max}) was the most sensitive indicator of fatigue induced by the basketball-specific protocol. It was hypothesized that (i) both vertical and horizontal F-V profiles would be decreased during and after the basketball-specific fatigue protocol, but (ii) low correlations were expected for the percentage changes in the F-V relationship parameters between the jumping and sprinting tasks.

Materials and methods

Subjects

Nineteen junior male basketball players (mean ± standard deviation [SD]; age = 16.0 ± 0.6 years, height: 178.4 ± 4.2 cm, body mass: 71.2 ± 9.8 kg) participated in this study. All subjects had at least one year of resistance training experience and had not sustained any musculoskeletal injuries for at least the past year. Subjects were also advised to refrain from engaging in any vigorous physical activity for at least 48 hours before each testing session. They and their legal guardians were informed about the study's purpose and procedures and they both gave their consent by signing an informed consent form before participating. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Ningbo University Institutional Review Board.

Study design

The subjects completed two sessions separated by at least 72 hours of rest. The first visit was designed to assess body composition (body mass and body height), push-off distance, and the load that enabled a squat jump (SJ) height of 12 cm. The push-off distance was determined as the difference between the extended lower limb length (perpendicular distance from the iliac crest to the toes with the three lower-limb joints fully extended) and the vertical distance between the iliac crest and the ground with knees flexed at 90º (Janicijevic, et al., 2020). An incremental loading test was implemented to determine the load that allowed a SJ height of 12 cm (63.7 ± 11.2 kg). The push-off distance was used in the second session when assessing the vertical F-V relationship, while the load that allowed a SJ height of 12 cm represented the heavy load used in the second session for the application of the two-point method (Janicijevic, et al., 2020)

The second session represented the main experimental session in which both the vertical and horizontal F-V profiles were measured at three time points: before (pre), during (mid) and after (post) undergoing a basketball-specific fatigue protocol. The warm-up routine for both sessions included 5-minute jogging, dynamic stretching exercises, three progressively faster 30-meter sprints, and five maximal unloaded and 20-kg loaded SJ. Both sessions were performed at the same time (± 1 hour) of the day for each participant and under similar environmental conditions.

Basketball-specific fatigue protocol

We used a modified version of the Loughborough Intermittent Shuttle Test (LIST) (Nicholas, Nuttall, &Williams, 2000), a protocol frequently employed in basketball fatigue studies (Afman, et al., 2014; Ansdell & Dekerle, 2020) (Figure 1). To mimic the four quarters of a basketball game, the exercise was structured into four blocks, with each block consisting of 11 cycles. Each cycle was composed of three sequences of 20-m walking at ≈ 1.54 m·s^{-1}, running at ≈ 3.49 m·s^{-1}, jogging at ≈ 2.79 m·s^{-1}, one 15-m maximum-effort sprint, and a basketball lay-up. After the first and third blocks, participants had a 2-minute rest period to simulate the break between quarters in basketball. A 10-minute rest, representing the half time interval, was provided immediately after the second (mid) assessment of the F-V profiles. Sprint times for each cycle were recorded using timing gates (Smart Speed, Fusion Sport, Australia), and the experimenter kept track of the number of successful lay-ups.

Vertical F-V profile modelling

The specific warm-up consisted of four progressive sets until reaching the heavy load used for the application of the two-point method. The two-point method has demonstrated a high validity for the assessment of the vertical F-V relationship (García-Ramos, Pérez-Castilla, & Jaric, 2021). Subjects performed two SJs with a plastic barbell of 0.5 kg and two SJs with the load associated with a jump height of ≈ 12 cm (63.7 ± 11.2 kg). A rest period of

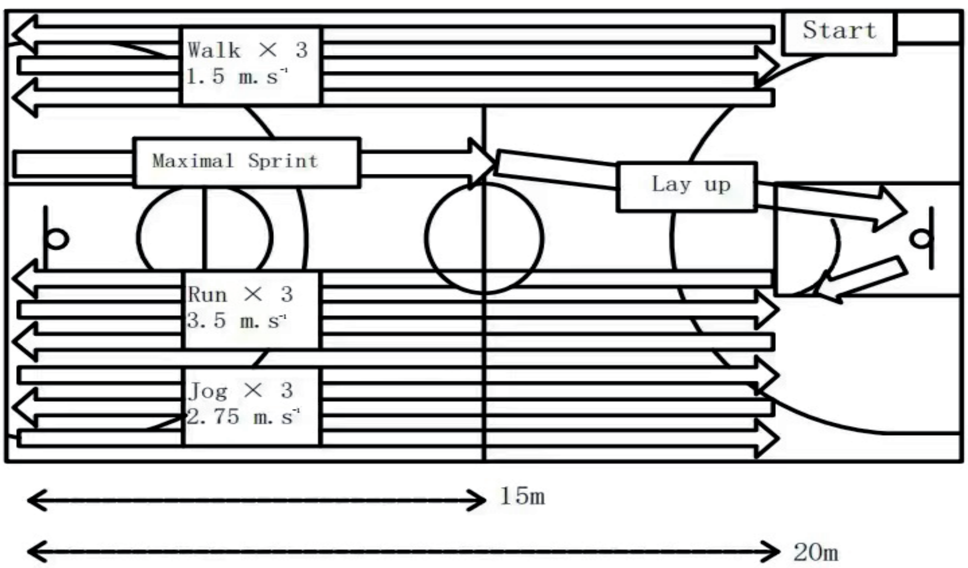

Figure 1. Modified version of the Loughborough Intermittent Shuttle Test (LIST).

one minute was implemented between successive jumps. Jump height was estimated by the flight time method at 240 frames per second using the validated My Jump 2 app on an iPhone 13 (Apple Inc., USA) (Bogataj, Pajek, Andrašić, & Trajković, 2020; Yingling, et al., 2018). The mean values of force and velocity were calculated using the simple method proposed by Samozino, Morin, Hintzy, and Belli (2008) considering three input variables: system mass, jump height and push-off distance. The mean values of force and velocity obtained under two loading conditions were used for the assessment of the F-V relationship through a linear model: $F(V) = F_0 - aV$, in which F_0 represented the force-intercept and a was the slope of the F-V relationship. The maximal theoretical velocity (v_0) corresponds to F_0/a. Finally, maximum power (P_{max}) was calculated as $P_{max} = F_0 \cdot v_0/4$. F_0 and P_{max} were normalized to body mass. Only the trial with the highest jump height of each load was used for the F-V relationship modelling.

Before each jump, subjects were instructed to stand upright and motionless in the center of the jumping area. To ensure a consistent knee angle of approximately 90º and control the push-off distance, a small chair was placed behind each subject (Z. Li, et al., 2024). Subjects were required to hold this initial position for about two seconds before starting the jump. Any countermovement was not allowed, and we strictly monitored to enforce this rule. Subjects were instructed to jump as high as possible during all trials.

Horizontal F-V profile modelling

Subjects were asked to execute two all-out 30-meter sprints separated by three minutes of rest. The sprints were initiated using a three-point stance. Timing gates were positioned at 0, 10, 20, and 30 meters along the sprint path. Subjects started with their heads 5-cm from the first beam and the front foot's toe 50 cm behind the starting line. The sprint with the shortest 30-meter time was used to assess the F-V profiles. A purpose-built Excel spreadsheet created by Morin and Samozino (2016) was used to calculate the parameters of the horizontal F-V profiles, including maximal theoretical force (F_0), maximal theoretical velocity (v_0), and maximal power output (P_{max}). This spreadsheet requires input of the sprint times recorded at each gate, along with the athlete's height, body mass, and the temperature and air pressure of the testing environment. F_0 and P_{max} were normalized to each participant's body mass.

Statistical analysis

Descriptive data are presented through means and SDs. The Shapiro-Wilk test confirmed the normal distribution of all vertical F-V relationship parameters (F_0, v_0, P_{max}) and the horizontal F_0 parameter ($p > .05$), but the rest of the horizontal F-V relationship parameters (v_0 and P_{max}) were not normally distributed ($p < .05$). In order to assess the effects of the basketball-specific fatigue protocol on the F-V relationship parameters, a one-way repeated-measures analysis of variance (ANOVA) (pre-fatigue *vs.* mid-fatigue *vs.* post-fatigue) with Bonferroni *post-hoc* corrections was applied to the normally distributed variables (vertical F_0, v_0, P_{max} and horizontal F_0), while the Friedman's test was applied to the variables which were not normally distributed (horizontal v_0 and P_{max}). When sphericity was violated ($p < .05$), the Greenhouse-Geisser correction was applied. The Cohen's d effect size (ES) was calculated to quantify the magnitude of the differences, and it was interpreted according to the scale proposed by Hopkins, Marshall, Batterham, and Hanin (2009): trivial (< 0.20), small (0.20-59), moderate (0.60-1.19), large (1.20-1.99) and very large (≥ 2.00).

Additionally, percentage differences of mid- and post-fatigue assessments with respect to the pre-fatigue assessment were calculated for different dependent variables ($\%\Delta = [\text{mid/post} - \text{pre}] / \text{pre} \times 100$). Paired samples t-tests and the Pearson's correlation coefficient (r) were used to compare the percentage differences between the jumping and sprinting tasks separately for each F-V relationship parameter (F_0, v_0, P_{max}). The magnitude of the r coefficient was interpreted according to the scale proposed by Hopkins et al. (2009): trivial (< 0.10), small (0.10-0.29), moderate (0.30-0.49), large (0.50-0.69), very large (0.70-0.89), and nearly perfect (≥ 0.90). All statistical analyses were performed using SPSS software version 22.0 (SPSS Inc., Chicago, IL, USA) and statistical significance was set at an alpha level of 0.05.

Results

All F-V relationship parameters, with the exception of the horizontal F_0, were significantly reduced compared to the pre-fatigue assessment (Table 1). Vertical P_{max} (ES = -0.48 to -0.80), horizontal P_{max} (ES = -0.58 to -1.28) and horizontal v_0 (ES = -0.81 to -0.98) showed larger reductions compared to the pre-fatigue assessment than vertical v_0 (ES = -0.19 to -0.27), vertical F_0 (ES = -0.16 to -0.25), and horizontal F_0 (ES = -0.11 to -0.30) (Figure 2). The differences between the mid- and post-fatigue assessment were negligible for vertical v_0, vertical F_0, and horizontal F_0 (ES < 0.20), but small differences in favor of the mid-fatigue assessment was observed for vertical P_{max}, horizontal P_{max}, and horizontal v_0 (ES = 0.30 to 0.49)

The percentage changes with respect to the pre-fatigue assessment did not significantly differ between the jumping and sprinting tasks for any F-V relationship parameter ($p \geq .364$). However, trivial to small correlations ($-0.23 \leq r \leq 0.19$) were

Table 1. Comparison of the force-velocity (F-V) relationship parameters obtained during the jumping and sprinting tasks before, during, and after undergoing a basketball-specific fatigue protocol

Task	Parameter	Time of assessment			ANOVA or Friedman test
		Pre-fatigue	Mid-fatigue	Post-fatigue	
Vertical F-V profile	F_0 (N·kg^{-1})	35.8 ± 6.0	34.9 ± 5.9	34.2 ± 7.0	F = 7.6; ***p* = .013**
	v_0 (m·s^{-1})	3.33 ± 0.87	3.17 ± 0.88	3.09 ± 0.90	F = 4.8; ***p* = .042**
	P_{max} (W·kg^{-1})	28.9 ± 4.5	26.7 ± 4.4	25.4 ± 4.3	F = 23.4; ***p* < .001**
Horizontal F-V profile	F_0 (N·kg^{-1})	7.58 ± 1.19	7.41 ± 1.78	7.17 ± 1.49	F = 1.0; *p* = .328
	v_0 (m·s^{-1})	8.82 ± 0.65	8.25 ± 0.76	7.97 ± 1.08	χ^2 = 8.3; ***p* = .016**
	P_{max} (W·kg^{-1})	16.6 ± 2.5	15.1 ± 2.9	14.0 ± 1.7	χ^2 = 19.9; ***p* < .001**

Note. ANOVA – analysis of variance; F_0 – maximal theoretical force; v_0 – maximal theoretical velocity, P_{max} – maximal power. Significant differences are emphasized in bold.

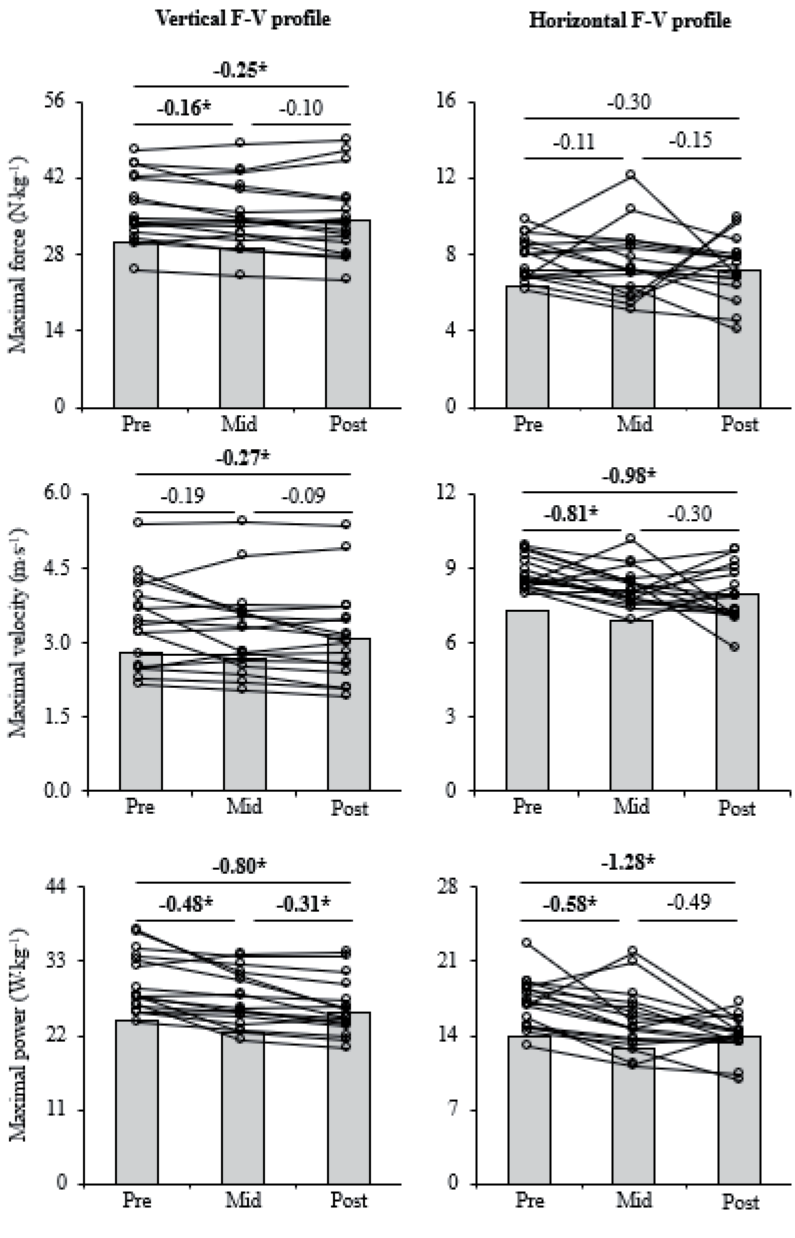

*Figure 2. Comparison of the force-velocity (F-V) relationship parameters collected during the jumping (left panels) and sprinting (right panels) tasks between the assessments performed before (pre), during (mid) and after (post) undergoing a basketball-specific fatigue protocol. Numbers represent the Cohen's d effect size. * – significant differences (p < .05).*

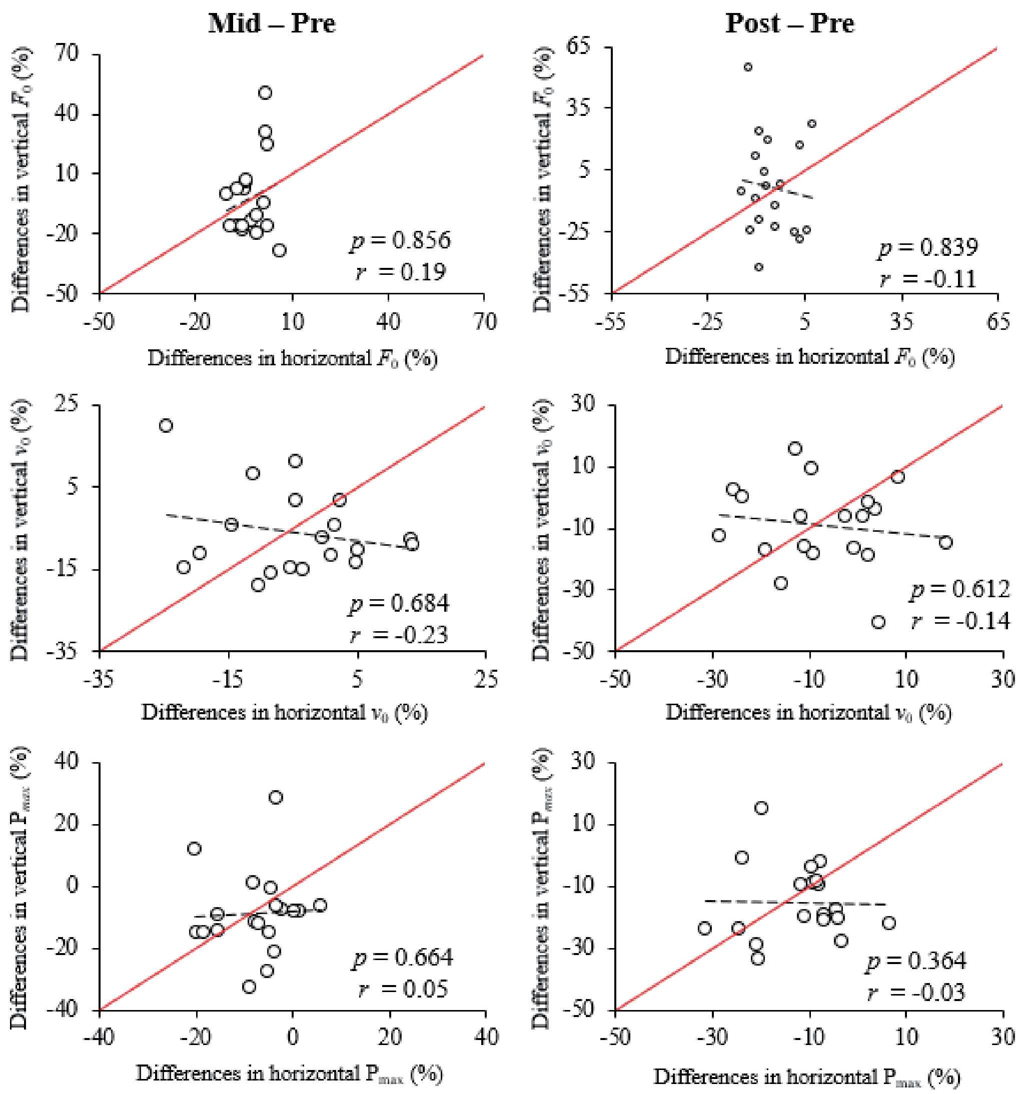

Figure 3. Comparison and association between the jumping and sprinting tasks for the percentage differences with respect to the pre-fatigue assessment in maximum force (F_0; upper panels), maximum velocity (v_0; middle panels) and maximum power (P_{max}; lower panels) at mid-fatigue (left panels) and post-fatigue (right panels) assessments. p – p-value obtained from paired sample's t tests; r – Pearson's correlation coefficient. The regression (dashed line) and identity (straight line) lines are depicted.

obtained for the percentage changes in the same F-V relationship parameters between the jumping and sprinting tasks (Figure 3).

Discussion and conclusions

This research was designed to determine the effects of a basketball-specific fatigue protocol on the changes in vertical and horizontal F-V profiles. All F-V parameters, except horizontal F_0, decreased significantly after the fatigue protocol. Vertical P_{max}, horizontal P_{max}, and horizontal v_0 showed the largest decrements. Regarding the comparison of the percentage change for the same F-V parameters obtained through the jumping and sprinting tasks, non-significant differences and trivial to small correlations were found. The results suggest that P_{max} should be the preferred parameter to detect fatigue after a basketball-specific fatigue protocol and emphasize the importance of assessing both jumping and sprinting tasks to gain a comprehensive understanding of the alterations in the lower-body muscle function after fatigue protocols.

Previous studies have indicated that P_{max} stands out as the most sensitive parameter for discerning the fatigue level induced by a particular task, as it encompasses variations in both F_0 and v_0 (García-Ramos, et al., 2018; Jiménez-Reyes, Cross, et al., 2018; Z. Li, et al., 2024). However, these findings have predominantly been documented within the context of resistance training and sprinting movements, leaving us uncertain about their applicability to the nuances of basketball matches. To generalize previous findings, this research compared the horizontal and vertical F-V profiles after a modified version of the LIST protocol. P_{max} also proved to be the most sensitive parameter in detecting the fatigue level caused by a basketball-specific fatigue protocol as it showed moderate to large decrements in both horizontal and vertical directions. Horizontal F_0 was the only variable that failed to detect fatigue induced by the LIST protocol, whereas the sensitivity of v_0 differed between the jumping and sprinting tasks, with moderate reductions for horizontal v_0 and trivial to small reductions for vertical v_0.

Although F_0 and v_0 were not as sensitive as P_{max} to reveal fatigue levels, previous studies found that F_0 and v_0 were capable of detecting selective fatigue under specific circumstances. For example, Z. Li et al. (2024) found that vertical v_0 had a considerable decrease, but not vertical F_0, after five repetitions of light-load ballistic squats. Additionally, a repeated sprint protocol impaired horizontal v_0 more than horizontal F_0 (Jiménez-Reyes, Cross, et al., 2018). Our findings are somewhat similar to the obtained in previous studies (Jiménez-Reyes, Cross, et al., 2018; Z. Li, et al., 2024). Due to the characteristics of the LIST protocol, it was expected that v_0 would experience greater decrements compared to F_0. This expectation was confirmed as no significant change was observed for horizontal F_0, whereas horizontal v_0 exhibited a moderate and significant decrement. Similarly, vertical F_0 showed a lesser decline compared to vertical v_0. The composition of the modified LIST, which primarily consisted of high repetitions of low-resistance movements like vertical jumping, horizontal running, and sprinting, likely contributed to these differences.

Several studies have explored the sprinting and jumping performance after different fatigue situations such as a match or Yo-Yo test (Fry, et al., 2024; Gathercole, Sporer, Stellingwerff, & Sleivert, et al., 2015; Janicijevic, et al., 2024; Pliauga, et al., 2015; Spillets, 2017). However, no study has directly compared in the same study the changes in F-V relationship parameters obtained through jumping and sprinting tasks. No significant differences were reported for the percentage changes with respect to the pre-fatigue assessment between jumping and sprinting tasks for any F-V parameter. This result suggests that the modified version of the LIST protocol led to similar fatigue in the horizontal and vertical directions of force application, which might be somewhat expected because the LIST protocol included a similar volume of high-intensity movements in both horizontal and vertical directions (15m sprint in the horizontal direction and lay-up in both the horizontal and vertical direction).

When compared to conventional fatigue monitoring tools such as heart rate and biochemical markers, what sets vertical jump height and sprinting time apart is their dual role in both sports performance and fatigue assessment (Edwards, et al., 2018). Additionally, several studies reported a high correlation between sprinting time and jumping height under fatigued and non-fatigued situations (Jiménez-Reyes, et al., 2019; Jiménez-Reyes, Samozino, et al., 2018; Lin, Shen, Zhang, Zhou, & Guo, 2023) Jiménez-Reyes et al. (2019) used countermovement jump (CMJ) height as a marker of fatigue during repeated sprint training and they found strong correlations of the decrement in CMJ height with lactate and ammonia concentrations. However, it is important to note that while CMJ height and sprint time are generally significantly correlated, the F-V relationship parameters derived from the jumping and sprinting tasks present weaker correlations (Jiménez-Reyes, Samozino, et al., 2018). In line with the findings by Jiménez-Reyes, Samozino, et al. (2018), we also found trivial to low correlations for the changes in the same F-V parameters after the modified LIST protocol. The different mechanisms involved in jumping and sprinting likely promote that their F-V parameters do not behave similarly under non-fatigue and fatigue situations. In line with our findings, sprinting performance and related variables, such as step length and step frequency, have shown significant correlations with unilateral jumping kinematics but not with bilateral vertical jumping kinematics (Mccurdy, et al., 2010). Therefore, to gain a more comprehensive understanding of players' fatigue levels, it is advisable to measure both vertical and horizontal F-V profiles in fatigue-inducing conditions.

Finally, some limitations should be acknowledged. Firstly, vertical and horizontal F-V profiles were tested using validated simple measurements and procedures, but direct force recordings were not obtained in this study. The reliability of the two-point method for evaluating vertical F-V profiles has not been evaluated in amateur youth athletes. However, it is worth noting that these athletes demonstrated sufficient strength, with an average vertical jump of at least 12 cm while carrying an external load exceeding 60 kg, thereby ensuring an adequate distance between the experimental points (García-Ramos, 2023). Horizontal F_0 was reported to be higher when assessed by the timing gate method (Haugen, et al., 2020). Additionally, although the participants were classified as junior players, their age range places them closer to cadet-level athletes. This may limit the generalizability of the findings to older juniors, young seniors, or adult athletes. Finally, the LIST protocol's limited inclusion of ball-handling movements, such as passing and change of direction, raised a concern as it could not fully replicate the demands of basketball games and accurately reflect their mechanical requirements

Both vertical and horizontal F-V profiles are effective in tracking fatigue resulting from a basketball-specific fatigue protocol. We discovered that P_{max}, a parameter combining F_0 and v_0 capacities, is the most sensitive indicator of fatigue levels. When we used vertical jumps for measurement, both F_0 and v_0 showed similar declines. However, in linear sprints, only v_0, not F_0, exhibited a significant decrease. This larger drop in horizontal v_0 compared to horizontal F_0 might be due to the protocol's emphasis on low-resistance, high-repetition tasks. Despite the overall reduction in F-V parameters (F_0, v_0, and P_{max}) being similar for both jumping and sprinting, the changes were not significantly correlated between both tasks. Therefore, practitioners are encouraged to assess F-V relationships during both jumping and sprinting to comprehensively monitor lower-body adaptations resulting from basketball training routines.

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Correspondence to:
Danica Janicijevic
E mail: janicijevic@nbu.edu.cn

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