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Determining power training needs using the force-velocity profile (imbalance) in elite female volleyball using different vertical jump

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Abstract: This study aimed to evaluate the Force-Velocity (Fv) profile of elite female volleyball players during the Squat Jump and Countermovement Jump to define the Fv profile of female athletes based on strength, power, and individual mechanical characteristics. The goal was to enhance training efficiency and improve performance in ballistic movements. For this study, we recruited 12 elite female volleyball players from the Montenegro U19 national team. The Fv profile was assessed in two types of muscle contractions: the Squat Jump (concentric contraction) and the Countermovement Jump (eccentric-concentric contraction) to determine Fv imbalance. First, the height of the jump was measured in the Squat Jump, followed by the Countermovement Jump. After that, the Fv profile was analyzed under both contraction types to assess potential imbalances. The results showed an Fv imbalance of 24.93% during the concentric muscle contraction and 29.71% during the eccentric-concentric muscle contraction. Based on these findings, it is suggested that training should prioritize enhancing strength capabilities while simultaneously addressing Fv imbalances. Reducing theoretical Fv imbalance could serve as a supplementary component of training to improve overall physical performance.

Keywords: multi-joint movements; jumping performance; muscle contraction; mechanical characteristics; ballistic movements; imbalance; physical performance

1. Introduction

Volleyball is one of the most popular team sports in the world, characterized by short and explosive movement patterns, quick and agile positioning, jumps, and blocks. Although a match can last up to three hours, volleyball is considered an anaerobic sport, with metabolic demands primarily met by the phosphagen energy system. In volleyball, a player's maximum height above the net is a crucial determinant of successful attacks and blocks, directly influencing performance development.
The key factors contributing to maximum height include anthropometric characteristics (such as body height and arm length) and the ability to perform a vertical jump [1]. Vertical jumping is considered one of the most important physical attributes in

volleyball, where emphasis is placed on methods for increasing vertical jump performance [2], as well as physical factors that contribute to its development specific to volleyball [3]. The use of force platforms and opto-jump systems enables the analysis of multi-joint movement patterns, which closely resemble volleyball-specific movements (e.g., closed kinetic chain activities and the stretch-shortening cycle). Additionally, key biomechanical variables such as acceleration, force, and impulse can be determined during jumping. Jump protocols that assess vertical displacement are widely used to measure jump height and lower limb strength [4, 51].

Among these protocols, the Countermovement Jump (CMJ) and Squat Jump (SJ) have been widely recognized as reliable methods for assessing jumping ability in recent years. Both CMJ and SJ involve a movement pattern that begins from a standing position and transitions into a sudden jump following a downward squat. However, while time-related factors such as the pause in the semi-squat position can influence performance in the SJ, they are eliminated in the CMJ [5]. Furthermore, measuring CMJ using a force platform or opto-jump system provides highly reliable data for evaluating mechanical power.

Within strength and power training, Force-Velocity (Fv) profiling has gained increasing attention as a tool for monitoring training adaptations and creating individualized training programs for athletes. The concept of Fv profiling is based on the fundamental properties of skeletal muscle, where an inverse relationship exists between force and velocity [6]. Recently, a new testing methodology has been proposed to provide a more comprehensive assessment of muscle performance determinants using Fv profiling [7]. Evaluating the Fv profile of these determinants allows for the identification of maximal mechanical capabilities in terms of force, velocity, and power during various ballistic movements, such as vertical jumps [8, 48].

In practice, athletes can perform maximal efforts against different loads while force and velocity are measured during vertical jumping or similar multi-joint movements. Based on these measurements, a linear regression line can be drawn to extrapolate the theoretical maximal force (F_0) (i.e., force at zero velocity) and theoretical maximal velocity (V_0) (i.e., velocity at zero force). From these values, theoretical maximal power (Pmax) can be calculated using the formula $Pmax = (F_0 \cdot V_0)/4$, while the slope of the Fv profile (SFV) is determined as F_0/V_0 [6]. Notably, each athlete has an optimal Fv slope (a specific combination of F_0 and V_0), which provides valuable information for designing individualized training programs [9, 50].

Most studies on Fv profiling have focused on male athletes [6,10,11]. As a result, research evaluating the Fv profile in female athletes remains limited in the literature. In the studies that do include female athletes, the SJ is typically used for Fv profile assessment [12]. The first study to define the Fv profile in CMJ, conducted by Petridis et al. [13], suggested that CMJ dynamics are more relevant to sports such as volleyball, as they involve consecutive eccentric-concentric muscle contractions, whereas SJ relies solely on concentric contractions.

To the best of the authors' knowledge, there is currently no scientific data comparing Fv values between individual jumps (SJ or CMJ) in women's volleyball. Therefore, the primary aim of this study was to evaluate the Fv profile of elite female volleyball players during the SJ and CMJ, to define their Fv profile based on strength, power, and individual mechanical characteristics. The findings of this study are intended to enhance training efficiency and improve performance in ballistic movements.

2. Materials and Methods

2.1. Participants

For this study, we recruited 12 elite female volleyball players from the Montenegro U19 national team (height: 180.08 ± 6.00 cm; mass: 65.67 ± 6.27 kg; body mass index: 20.20 ± 1.10 kg/m²; body fat: 18.89 ± 3.70%). The study was conducted during the preparation period for the European Championship qualifications.

To ensure consistency in physical condition before testing, players were instructed to avoid resistance exercises and any highly exhaustive training for two days prior to the measurements. Additionally, they were asked to maintain their regular eating habits and abstain from alcohol consumption during this period.

All participants compete in the first national league, the highest competitive level in Montenegro. They reported having participated in regular training for at least five years, attending 5.7 ± 1.2 training sessions per week, and consistently performing full-body resistance exercises at least twice a week.

The inclusion criteria required that players:

- Had been part of the first team for at least six months,
- Had completed a full preparatory period with the team,
- Had remained injury-free for the past six months,
- Had played at least one half-season before testing.

The exclusion criteria included:

- Players recovering from acute or chronic injuries,
- Players who had not completed the full preparatory period.

All participants were informed about the experimental procedures and provided written informed consent before participating in the study. For underage participants, consent was obtained from their parents or legal guardians.

2.2. Study design

This was a cross-sectional study. Participants completed the testing procedures as part of their routine assessments; therefore, no separate familiarization session was conducted.

The warm-up protocol consisted of:

- 10 minutes of light running on a closed track,
- 5 minutes of dynamic stretching,
- 5 minutes of bodyweight resistance exercises (squats, lunges, push-ups),
- 3 minutes of activation exercises (vertical jumps).

Two types of vertical jumps were tested: the Squat Jump (SJ) and the Countermovement Jump (CMJ). The CMJ was assessed using the Optojump system [14]. Jump values were recorded by positioning the player within a designated area covered by Optojump sensors. From an upright position, at the sound of a signal, the participant—keeping their hands on their hips—descended into a semi-squat before jumping as high as possible. Each participant performed three technically correct jumps, and the best result was used for analysis.

The SJ was also tested using the Optojump system. In this test, the participant assumed a semi-squat position with hands on their hips and held it for two seconds. At the sound of a signal, the participant jumped vertically from the starting position. Each test was repeated three times, and the best-achieved value was used for analysis [14, 46].

Following the jump tests, the Force-Velocity (Fv) profile was assessed for both the SJ and CMJ.

This study was conducted in accordance with the Declaration of Helsinki, with all authors contributing equally alongside the first author.

2.3. Assessment of Force-Velocity in Squat and Countermovement Jumps

Before the jumping assessment, the players' leg length was measured in two ways:

1. From the anterior superior iliac spine to the big toe, with the leg fully extended.
2. From the floor to the upper anterior superior iliac spine, with the knee bent at 90 degrees.

The latter measurement was used as a reference point for jump depth, which was monitored by the examiner.

The female players performed vertical jumps with additional weight. External load was applied using an Olympic bar (20 kg). The load range varied from a jump without additional weight (body mass only, with a plastic stick placed on the shoulders) to the maximum load with which the participants could safely and technically perform a jump—defined as the point where jump height dropped below 10 cm.

Additional load was progressively increased by 4 kg after each jump, except for the first loaded jump, which was performed with the Olympic bar alone [15]. Weighted jumps were executed using a Smith machine, which allowed the bar to move vertically along a fixed path. Each player performed two weighted jump attempts, with two minutes of passive rest between attempts and 3–4 minutes of rest between load increments. For statistical analysis, the best value for each type of jump was recorded. Verbal motivation and encouragement were provided to maximize effort in each jump [13, 52].

The theoretically optimal Force-Velocity (Fv) profile, which maximizes jumping performance, was calculated based on Pmax and push-off distance (hpo). Push-off distance was defined as the vertical displacement of the center of mass from the lowest point before take-off and was derived from the vertical displacement-time-ground contact curve [16,17, 49].

Fvimb for each volleyball player was calculated as the percentage difference (%) between the measured (Sfv) and the optimal (Sfvopt) Fv slope, normalized for body mass ($N \cdot s \cdot Kg^{-1} \cdot m^{-1}$) [16]. Based on previously published assessments of FVimb, the following categories were defined:

- Well-balanced: 0 ± 10%
- Low deficit: 10–40%
- High deficit: >40% in the Fv profile [18].

The obtained data on average force and average velocity for each load in the Fv profile were analyzed using linear regression, with force data plotted on the X-axis and velocity data on the Y-axis [15, 47].

2.4. Statistical Analysis

All data collected in this study were analyzed using descriptive and comparative statistical methods.

For descriptive statistics, the mean and standard deviation were calculated for each variable. The normality of variable distribution was assessed using two procedures:

- Skewness analysis to evaluate asymmetry,
- Kurtosis analysis to assess homogeneity.

For comparative statistics, a discriminant parametric procedure was applied. Specifically, a one-way analysis of variance (ANOVA) with a post hoc test was conducted to determine differences in the Force-Velocity (Fv) profile.

All statistical analyses were performed using SPSS software (version 26.0, IBM, United States), with a significance level set at $p < 0.05$.

3. Results

Tables 1 and 2 present the descriptive parameters of the Force-Velocity (Fv) profile in the Squat Jump (SJ) and Countermovement Jump (CMJ).

The results of skewness and kurtosis indicated that the data exhibited symmetry and homogeneity. Additionally, the distribution of the results followed a normal distribution, confirming the appropriateness of parametric statistical analyses.

Table 1. Squat jump - Force-velocity profile

Variables	Mean ± SD	95% CI	
		Lower	Upper
Force (Fo) (N/kg)	22.05 ± 1.72	21.06	23.05
Velocity (Vo) (m·s^{-1})	2.08 ± .17	1.98	2.18
Theoretical maximal power (Pmax)(W/kg)	11.45 ± .72	11.03	11.87
Push-off distance (h_{po}) (m)	30.71 ± 3.53	28.67	32.76
Slope of the Fv profile (Sfv) (Ns/m/kg)	-10.69 ± 1.65	-11.65	-9.73
Optimal Sfv (Sfv_{opt})(Ns/m/kg)	-8.58 ± .54	-8.89	-8.27
Fv imbalance velocity deficit (FV_{imb}) (%)	24.93 ± 19.48	13.68	36.18
Hight maximum (h_{max}) (m)	26.64 ± 2.93	24.9	28.25

SD – standard deviation, CI – interval of confidence

Analyzing the results in Table 1, the Force-Velocity imbalance (Fvimb) in the Squat Jump (SJ) was 24.93%.

Referring to Figure 1, an individual analysis showed that:

- 5 female players had a well-balanced Fv profile (within ±10% of the optimal).
- 5 female players exhibited a low deficit in the Fv profile (10–40% of the optimal).
- 2 female players demonstrated a high deficit in the Fv profile (>40% of the optimal).

Slightly worse results were observed in the Countermovement Jump (CMJ), where the Fvimb was 29.71%, as presented in Table 2 and Figure 1. Specifically:

- 2 female players had a well-balanced Fv profile (within ±10% of the optimal).
- 8 female players exhibited a low deficit in the Fv profile (10–40% of the optimal).
- 2 female players demonstrated a high deficit in the Fv profile (>40% of the optimal).

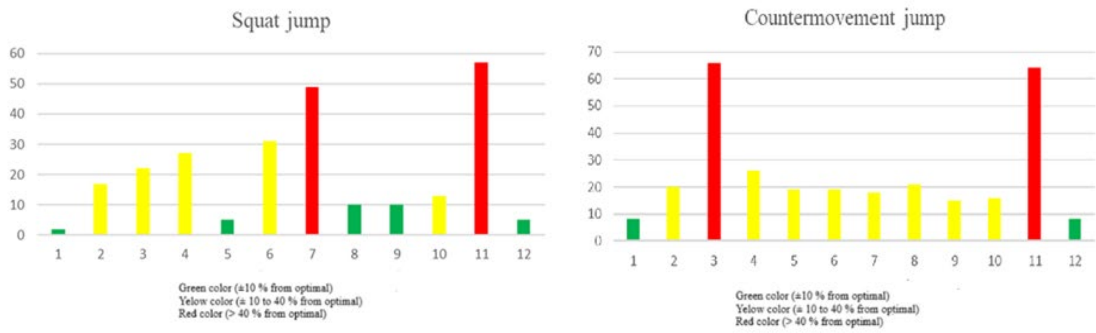

Figure 1. FVimb in female volleyball players

Table 2. Countermovement jump – Force-velocity profile

Variables	Mean ± SD	95% CI	
		Lower	Upper
Force (Fo) (N/kg)	22.49 ± 1.86	21.41	23.56
Velocity (Vo) ($m \cdot s^{-1}$)	2.05 ± .16	1.95	2.14
Theoretical maximal power (Pmax)(W/kg)	11.41 ± .75	11.10	11.86
Push-off distance (h_{po}) (m)	30.71 ± 3.53	28.67	32.76
Slope of the Fv profile (Sfv) (Ns/m/kg)	-11.07 ± 1.84	-12.13	-10.0
Optimal Sfv (Sfv_{opt})(Ns/m/kg)	-8.55 ± .49	-8.83	-8.26
Fv imbalance velocity deficit (FV_{imb}) (%)	29.71 ± 21.69	17.19	42.24
Hight maximum (h_{max}) (m)	26.65 ± 2.85	25.1	28.44

SD – standard deviation, CI – interval of confidence

Figure 1 illustrates the Force-Velocity imbalance (Fvimb) (velocity deficit) for each volleyball player individually in both Squat Jump (SJ) and Countermovement Jump (CMJ).
The results of the ANOVA indicate a statistically significant difference ($p < 0.05$) between the variables in the Fv profile across the two different jump types, as presented in Table 3.

Table 3. Differences between SJ and CMJ in force-velocity

Variables	Jumps	Mean ± SD	F	p
Force (Fo) (N/kg)	SJ	22.05 ± 1.72	.414	.526
	CMJ	22.49 ± 1.86		
Velocity (Vo) ($m \cdot s^{-1}$)	SJ	2.08 ± .17	.251	.621
	CMJ	2.05 ± .16		
Theoretical maximal power (Pmax)(W/kg)	SJ	11.45 ± .72	.012	.914
	CMJ	11.41 ± .75		
Slope of the Fv profile (Sfv) (Ns/m/kg)	SJ	-10.69 ± 1.65	.326	.573
	CMJ	-11.07 ± 1.84		
Optimal Sfv (Sfv_{opt})(Ns/m/kg)	SJ	-8.58 ± .54	.033	.857
	CMJ	-8.55 ± .49		
Fv imbalance velocity deficit (FV_{imb}) (%)	SJ	24.93 ± 19.48	1.377	.040
	CMJ	29.71 ± 21.69		
Hight maximum (h_{max}) (m)	SJ	26.64 ± 2.93	.031	.863
	CMJ	26.65 ± 2.85		

SJ - squat jump, CMJ - Countermovement jump, F – value of Fisher test, p – lever of probability

4. Discussion

4.1. Theoretical implications

The primary aim of this study was to evaluate the Force-Velocity (Fv) profile of elite female volleyball players during the Squat Jump (SJ) and Countermovement Jump (CMJ). The main concept behind establishing the athletes' Fv profile is that strength and power training tailored to individual mechanical characteristics has been suggested to enhance training effectiveness and performance in ballistic movements [7]. Our results revealed low to high velocity deficits in most of the players. Optimally developed Fv profile values (±10%) were observed in 41.6% of the athletes, while 41.6% exhibited a low Fv profile deficit (10–40%), and 16.67% had a high Fv profile deficit (>40%) (Figure 1). In CMJ, a well-balanced Fv profile (±10%) was recorded in 16.67% of athletes, while 66.66% displayed a low deficit (10–40%), and 16.67% had a high deficit (>40%).

The results obtained in this study can be compared with previous research, where a lack of force has been commonly reported in female athletes. In contrast to our findings, Petridis et al. [13], in CMJ, reported that 11.1% of female players had a well-balanced Fv profile, while 75% had a low force deficit, and 13.9% had a high force deficit. Similarly, Pelinkas et al. [19], in a study of 27 female players, reported that 12 players exhibited a velocity deficit, while 15 players showed a force deficit. Comparable results have also been found in other sports. Marcote-Pequeno et al. [9], using SJ tests in female soccer players, reported an Fv profile deficit of 64.5%, while Jimenez-Reyes et al. [20] found an Fv profile deficit of 43.7% in female track and field athletes.

The higher prevalence of velocity deficit found in this study likely reflects the strength training methods to which the athletes are accustomed. Generally, athletes who train with high external loads tend to develop better force qualities, leading to a force-oriented Fv profile [13], which aligns with our findings.

Discussions with the strength and conditioning coach revealed that the athletes followed a training program twice per week, which primarily included horizontal pushing exercises. These exercises minimize the influence of gravity, explaining why power output during maximal efforts is less dependent on muscle strength when exercises do not involve gravity [21]. This finding is consistent with previous research [22], which suggests that horizontal pushing exercises increase velocity deficits, further supporting our results.

To improve velocity capabilities and reduce Fvimb, overspeed exercises may be particularly effective. These exercises eliminate the gravitational constraint, allowing athletes to achieve lower-limb extension velocities that are 20–30% higher than the take-off velocity of an SJ [23]. Such exercises are beneficial for developing explosive muscle contractions, including rate of force development and maximal velocity [24]. This results in an earlier force-time curve shift (50–100 ms) [25,26], emphasizing the importance of training with external resistance forces lower than body weight. Future research should explore whether lighter loads yield greater training effects, as previous studies have shown the benefits of training without gravitational negative loads [23,27-29].

Push-off distance (hpo) also played a significant role in the differences in Fv profile (Sfv_opt and Fvimb) between SJ and CMJ. Since hpo is used to determine the optimal Fv relationship, its magnitude directly affects Fv imbalance. A shorter hpo increases the steepness of the optimal Fv slope, thereby increasing the difference between measured and optimal Fvslope, resulting in a larger Fvimb. Conversely, a longer hpo decreases the steepness of the optimal Fvslope, leading to a less imbalanced Fv profile [13].

The hpo height characterizes the usual or optimal range of lower-limb extension for an individual. This range depends on morphological characteristics and sport-specific demands, both of which can be modified through training. This further highlights the importance of Fvimb in CMJ performance, which can be improved by adjusting training approaches.

Historically, a "one-size-fits-all" approach has been widely used in strength training programs, yielding positive effects on jump performance. However, this approach has limitations. Training content that does not consider individual physical needs or adaptation responses can lead to high variability in training effectiveness [18].

Jimenez-Reyes et al. [22] compared traditional load training (same for all athletes) with individualized training based on Fvimb and optimal Fv profile. Their findings revealed that while the "one-size-fits-all" approach resulted in variable responses, individualized training led to consistent improvements in jump height, with all athletes showing progress beyond the minimum worthwhile change threshold.

A statistically significant difference in Fvimb between CMJ and SJ was recorded in this study. Several possible explanations for this discrepancy include:

1. Lack of Familiarity with SJ:
   - Athletes may be less accustomed to performing SJ, making it harder to control movement.
   - Poor coordination can limit jump height, making it submaximal compared to CMJ.
2. Delayed Force Development in SJ:
   - In SJ, muscles may not achieve high force levels before the onset of concentric contraction.
   - Muscle force development takes time due to neural stimulation, excitation dynamics, and contractile element interactions [35-38].
   - This delay reduces effective force output, limiting performance.
3. Elastic Energy Storage in CMJ:
   - During CMJ, muscles undergo pre-stretch, storing energy in the serial elastic elements, which is later reused to enhance the concentric phase [41].
4. Neuromuscular Activation in CMJ:
   - The stretching motion in CMJ triggers spinal reflexes, increasing muscle activation levels beyond those seen in SJ.
   - This allows for greater force production during the concentric phase, improving performance.
5. Potentiation Effect of Pre-Stretching in CMJ:
   - Pre-stretching alters the contractile properties of the muscle, increasing force output beyond what is achievable in SJ [35,42,43].

Finally, it is important to highlight that the volleyball players in this study were undergoing a two-month intensive training period with the national team, involving high training loads. During this period, training was primarily hypertrophy-focused, which may have:

- Limited their ability to maximize velocity and high-power output.
- Increased accumulated fatigue, negatively affecting jump performance and Fv profile values.

This study highlights the importance of individualized strength and power training in addressing Fvimb and optimizing jump performance. The findings reinforce the limitations of a "one-size-fits-all" training approach, suggesting that tailored interventions based on individual Fv profiles can significantly improve athletic performance in elite female volleyball players.

4.2. Practical applications

The results of this study highlight the necessity of individualized training, not only in terms of training content but also training duration. Incorporating specific training duration as a parameter will provide a more comprehensive understanding of effective training strategies tailored to individual needs.

A study by Jimenez-Reyes et al. [22] found a significant correlation between time required to reach the optimal Fv profile and Fvimb ($r = 0.82$, $p < 0.01$). This suggests that the greater the Fvimb, the longer the time needed to achieve an optimal Fv profile.

From a practical standpoint, these findings allow for recommendations on training duration based on the athlete's initial Fvimb. Given the ease of testing throughout the season—which includes limb extension, Pmax measurements, and jump assessments with minimal additional loads [17,44]—it is recommended to continuously monitor Fvimb. This will help determine when an athlete should transition between training subgroups, allowing for adjustments in training content. Additionally, regular Fv assessments enable training duration modifications based on the athlete's adaptation rate.

Since individual athletes adapt at different rates, frequent evaluations will facilitate more effective training periodization and better adaptation to each athlete's response to training. It is recommended to conduct these assessments every 1 to 3 weeks, though they can be performed more frequently when necessary. Rapid assessments can be conducted using 2-load tests, allowing for quick and efficient Fv evaluations when needed [44].

4.3. Strengths and limitations of the study

The findings of this study provide valuable insights and practical examples derived from specific training experiences, guiding strength and conditioning coaches toward individualized and more effective monitoring and periodization of training.

However, this study has several limitations. The primary limitation is the lack of precise training data, preventing clear conclusions regarding the Fv profile of female volleyball players. As a result, the findings cannot be generalized or directly applied to other athletes.

Additionally, the players in this study were members of different clubs, each following distinct training programs, which made it difficult to collect consistent training data. Another limitation stems from variations within the microcycle, as the training or rest days preceding the tests may have influenced the players' Fv profiles.

Finally, there is no available data on the maximal strength levels of the female volleyball players in this study. As a result, we cannot establish a direct relationship between maximum strength and the Fv profile.

5. Conclusions

In the Squat Jump (SJ), 5 female volleyball players demonstrated a well-balanced Fv profile (within ±10% of the optimal value), while 5 players exhibited a low deficit in the Fv profile (10–40% of the optimal). In contrast, 2 players showed a high deficit in the Fv profile (>40% of the optimal).

Slightly worse results were recorded in the Countermovement Jump (CMJ). Specifically, a well-balanced profile (within ±10% of the optimal) was observed in only 2 players, while 8 players exhibited a low deficit (10–40% of the optimal), and 2 players recorded a high deficit (>40% of the optimal).

Overall, these findings suggest that training should prioritize enhancing strength capabilities, while reducing theoretical Fvimb could serve as a supplementary component to improve basic physical performance. From a practical perspective, the focus should be on shifting the entire Fv curve to the right and improving power output across the entire Fv continuum. Correcting theoretical Fvimb should be considered a secondary goal [45].

Future research should explore the optimal level of maximal strength required to optimize the Fv profile in elite female volleyball players.

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