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Section I – Kinesiology

Impact of Overestimation Bias in the Peak Velocity Method on Jump Height and Force-Velocity Profiling

by

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We aimed to validate the Peak Velocity Method (PVM), independent of device-related errors, for measuring jump height and force-velocity profiles. Ten men (age: 20 ± 1 years, body height: 173.5 ± 4.7 cm, body mass: 76.2 ± 8.3 kg) performed two countermovement jumps under body mass (BM) and loaded conditions (BM + 32 kg and 1.6, 1.8, 2.0, and 2.2 BM). The jumps were analyzed using a force plate. Peak and take-off velocities were obtained from the same jump and substituted into the impulse-momentum method (IMM) equation to calculate jump height. The method using peak velocity was defined as the peak velocity method (PVM), while the method using take-off velocity was defined as the impulse-momentum method (IMM). The force-velocity profile variables were also derived using both methods. Compared with the IMM, the PVM consistently exhibited a positive fixed bias in jump height (0.036 ± 0.008 m) and force-velocity variables, with overestimation becoming more pronounced under loaded conditions (0.043–0.044 ± 0.009–0.010 m). Proportional bias was also evident in BM and force-velocity variables. Furthermore, force-velocity profile classification was affected by the PVM, misidentifying participants as transitioning from force deficit to velocity deficit. These findings indicate that, although widely adopted in inertial measurement devices due to its convenience, the PVM introduces measurable errors within the strict experimental conditions of this study and may be unsuitable for accurately assessing jump heights (Hedges' g = 0.61–1.82) and force-velocity profiles (Hedges' g = 1.00–10.81).

***Keywords**: jump performance; measurement method; loaded jump; countermovement jump; validity*

Introduction

Jump height is closely related to fundamental abilities underpinning sports performance, such as sprinting (r = 0.82 in elite sprinters, Loturco et al., 2015) and change-of-direction ability (r = 0.41, based on a recent meta-analysis, Chen et al., 2023). In sports like volleyball (Sattler et al., 2015) and basketball (Spiteri et al., 2019), where the maximum height of the center of mass directly affects performance, enhancing jump height has been a key focus for strength coaches. Additionally, monitoring jump height provides insights into neuromuscular fatigue (Claudino et al., 2017). Therefore, measuring jump height holds significant importance.

Measuring jump height offers advantages, such as requiring less space than sprinting or change-of-direction running and causing less physical strain than assessing maximum lift weight in exercises like squats. Furthermore, jump height is recognized for its high reliability (intraclass correlation coefficient: ICC = 0.88–0.91), as reported in a systematic review involving athletes and resistance-trained individuals under standardized laboratory conditions (Xu et al., 2023), making it a valuable metric for assessing physical performance. Consequently, several methods for measuring jump height have been developed. Among these, the highly acceptable method, based on the impulse-momentum theory (Xu et al., 2023), is calculated using Newtonian mechanics. However, this approach requires measuring ground reaction forces on an expensive force plate to determine the velocity at the instant the feet leave the ground, which can be impractical in athletic settings. To

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address this issue, methods using inertial measurement units, which are more affordable and easier to implement in sports environments, were developed (Casartelli et al., 2010; Comyns et al., 2023; Jimenez-Olmedo et al., 2023; Rantalainen et al., 2020). Two primary methods exist for measuring jump height using inertial measurement units. The first estimates jump height by assuming that the acceleration acting on the body's center of gravity immediately after the take-off equals gravitational acceleration. It calculates flight time as the period from this point until the acceleration falls below gravitational acceleration upon landing (Rantalainen et al., 2020; Xu et al., 2023). The calculated flight time is then substituted into the flight time method formula (Rantalainen et al., 2020; Xu et al., 2023). The second method, known as the peak velocity estimation method (PVM), determines jump height by substituting the peak vertical velocity during the jump as the take-off velocity and applying it to the impulse-momentum formula (Jimenez-Olmedo et al., 2023; Rantalainen et al., 2020). The flight time method has also been validated for its validity and reliability using other devices (Xu et al., 2023), such as force platforms, jump mats, and motion capture systems. Consequently, irrespective of the measurement device, the flight time method is recognized as a valid approach for measuring jump height. In contrast, the PVM has been investigated primarily using inertial measurement units, with limited studies comparing it against other devices (Casartelli et al., 2010; Jimenez-Olmedo et al., 2023; Rantalainen et al., 2018). This suggests that errors in PVM measurements may stem not only from device-dependent biases in inertial measurement units, but also from potential interactions between the intrinsic limitations of the PVM and device-specific inaccuracies, leaving the validity of the PVM itself unverified. Establishing its validity requires comparing jump heights calculated from the same jump using the PVM with those obtained via the impulse-momentum method (IMM) on a force plate. Therefore, it remains unclear whether the overestimations observed in previous studies are attributable to intrinsic limitations of the PVM itself or to device-related factors inherent to inertial measurement units. In this study, we did not simply test whether PVM- and IMM-derived jump heights differed, but aimed to quantify the extent of this difference, assess its acceptability in practical contexts, and examine whether it varied across different loading conditions. These considerations provide the rationale for applying statistical tests to investigate the nature and consistency of the observed discrepancy. Addressing this gap is essential for determining whether the PVM can be reliably used across different measurement platforms.

It is generally understood that the peak velocity of the body's center of gravity during a jump occurs just before the take-off and exceeds the velocity at the take-off (Cormie et al., 2008; McMahon et al., 2017). Thus, using peak velocity as the take-off velocity in calculations may lead to overestimations. This potential overestimation applies to both the body mass (BM) and loaded jumps. Notably, Cormie et al. (2008) observed that the difference between peak velocity and take-off velocity varied between loaded and BM jumps, suggesting that the degree of overestimation differed accordingly. However, this aspect remains unclear. It has been recognized that assessing lower limb extension power using only BM jumps is inadequate (Morin et al., 2019). For this reason, it is recommended to include jumps with various loads to calculate the force-velocity profile in athletic settings (Morin and Samozino, 2016; Samozino et al., 2012). Training interventions based on this profile have proven effective in improving jump height (Jiménez-Reyes et al., 2017; Simpson et al., 2021). However, a recent systematic review and meta-analysis found that individualized F-V-profile-based training was more effective in reducing F-V imbalance, but was not consistently superior to non-individualized training for improving jump height or P_{max}, except for jump height in athletes with a velocity deficit (Li et al., 2026). When determining the force-velocity profile, discrepancies between peak and take-off velocities during loaded jumps could alter the profile slope, potentially leading to significant errors in theoretical maximum force and velocity estimates.

Therefore, we aimed to validate the accuracy of the PVM by comparing it with the IMM obtained from a force plate, thereby eliminating device-dependent errors from inertial measurement units and other devices. Additionally, we sought to investigate the extent of overestimation in both BM and loaded jumps and to examine the impact of the PVM on the force-

velocity profile. The hypothesis was that the PVM would overestimate jump heights in both BM and loaded jumps compared to the IMM, with varying degrees of overestimation. Furthermore, it was hypothesized that the PVM would significantly overestimate the force-velocity profile and alter its slope.

Methods

Participants

The study included 10 healthy men (mean age: 20 ± 1 years; BM: 76.2 ± 8.3 kg; body height: 173.5 ± 4.7 cm), all of whom had at least one year of weight and jump training experience and engaged in weight training two to four times per week. Participants were collegiate athletes from American football, ice hockey, and rugby teams. Each participant was able to safely perform a countermovement jump (CMJ) with a load equivalent to 2.2 BM (Nishiumi and Hirose, 2024a) and had no musculoskeletal disorders. The sample size was determined through an a priori power analysis using G*Power 3.1 software (Heinrich-Heine-University, Dusseldorf, North Rhine-Westphalia, Germany). For this analysis, the statistical power was set at 0.8 (Cohen, 1988). Effect size *f* and the significance level were set at 1.32 (Rantalainen et al., 2018) and 0.008 (Bonferroni correction applied), respectively, for the paired *t*-test, and at 0.4 and 0.05, respectively, for the one-way ANOVA. The analysis indicated that 10 participants were required to meet the statistical power condition. The study received approval from the Waseda University Institutional Review Board, Saitama, Japan (protocol code: 2021-089; approval date: 17 June 2021) and was conducted in accordance with the principles of the Declaration of Helsinki. All participants were informed verbally and in writing about the potential risks and provided written informed consent prior to participation.

Procedure

The study was conducted over two separate days. On the first day, participants familiarized themselves with both BM and loaded CMJs. The second day was designated for data collection. On day 1, participants completed a 10-min warm-up consisting of cycling and dynamic stretching. The stretching routine included five repetitions of quadriceps and hip extensor stretches per side, followed by ten repetitions of overhead lunges and thoracic rotation exercises on both sides. Participants then practiced BM CMJs and five loaded CMJs (BM + 32 kg and 1.6, 1.8, 2.0, and 2.2 BM). The minimum load was set at 32 kg due to equipment limitations; the Smith machine used in this study could not be loaded with less than 32 kg. A minimum of two repetitions per load were performed using the same Smith machine as during subsequent testing, ensuring familiarity with the required countermovement depth (90° knee flexion). On day 2, after body height and mass measurements, participants repeated the same warm-up as on day 1 and performed the BM CMJ and five loaded CMJs. All jumps were measured twice using force plates. A gap of three days to one week was maintained between the two sessions to prevent fatigue. Participants were instructed to refrain from lower-body resistance training during this period (Thomas et al., 2018).

Exercise Measurements

The BM CMJ was performed with a 0.5-kg carbon bar placed on the participants' shoulders. For the loaded CMJs (BM + 32 kg and 1.6, 1.8, 2.0, and 2.2 BM), the same Smith machine (KEISER Inc., Fresno, CA, United States) as used during the familiarization session was utilized. Participants held the barbell in a high-bar position (above the trapezius), standing with their feet shoulder-width apart and toes slightly outward. They descended into a squat until the knee joint reached 90°. A timing gate (VoltOnoSprint; S-CADE Inc., Tokyo, Japan) positioned under the hip emitted a sound upon reaching this depth (Nishiumi and Hirose, 2024b). Participants were instructed before each trial to "squat as fast as possible, then jump as fast as possible". As part of the warm-up, participants performed two sets of three BM CMJs and one CMJ at each load. The BM CMJ was measured first, followed by the loaded CMJs presented in randomized order. A minimum rest interval of 2 min was provided between trials. Any trial where the countermovement depth did not reach 90° at the knee joint was discarded and repeated after a 2-min rest interval.

Measurement Equipment and Data Analysis

Vertical ground reaction forces during CMJs were recorded at a sampling rate of 1000 Hz using a force plate (9287CA, Kistler Japan Inc.,

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Kanagawa, Japan). Waveform data were processed using a low-pass filter set at 50 Hz (Harry et al., 2022). Before each trial, participants remained stationary on the force plate for 1 s to capture the system mass (add the body mass and external load, then divide by gravitational acceleration). The center of mass of the system was calculated using the trapezoidal rule (Linthorne, 2001). Specifically, the ground reaction force was divided by the system mass to determine acceleration, which was then integrated to derive velocity and further integrated to calculate displacement. The CMJ phases were divided based on previous research (Harry et al., 2020) as follows: 1) downward phase: from when the force decreased by 2.5% from the static force; and 2) propulsive phase: from when the velocity became positive until the ground reaction force dropped below 20 N. Jump height was calculated using two methods: the IMM and the PVM. In the IMM, the take-off velocity of the center of mass was calculated from the impulse during the propulsive phase. The jump height was determined using the equation:

$$h = \frac{TOV^2}{2g}$$

In the PVM, the peak velocity during the propulsive phase was considered the take-off velocity, and the same equation was used to calculate jump height.

Force-velocity profiles during the jump were obtained as described by Samozino et al. (2012). The theoretical maximum force (i.e., force intercept [F0]), theoretical maximum velocity (i.e., velocity intercept [V0]), maximum power (P_{max}), slope of the profile (Sfv), and profile imbalance (FVimb) were calculated by inputting the BM, external load, jump height, and push-off distance for each CMJ condition into an Excel-based tool developed by Samozino et al. (2012). The push-off distance was defined as the displacement of the center of mass from the lowest point during the downward phase to the point of the take-off during the propulsive phase. It should be noted that push-off distance was derived using double integration, which might introduce relatively large errors due to the accumulation of small measurement inaccuracies.

Statistical Analyses

The values are presented as means and standard deviations. Statistical analyses were performed using SPSS. Data normality was assessed using the Shapiro-Wilk test (normality was confirmed for all variables). The within-subject reliability of the peak velocity and take-off velocity was assessed using the ICC (1, 1) and the coefficient of variation (CV). An ICC of ≥ 0.75 (Koo and Li, 2016) and a CV of <10% (Cormack et al., 2008) were considered acceptable thresholds for reliability.

The jump heights and force-velocity profile variables measured by the PVM and the IMM were compared within each load condition using paired *t*-tests. To control for the increased risk of Type I error associated with multiple comparisons, Bonferroni correction was applied. Accordingly, the significance level was set at $p < 0.008$. Effect sizes were calculated as Hedges' g (Hedges, 1981) and interpreted as small (>0.2), medium (>0.5), and large (>0.8).

Mean differences in jump heights across the six load conditions were analyzed using a one-way repeated measures ANOVA (significance level $p < 0.05$), followed by Bonferroni post-hoc comparisons. Effect size was determined using partial η^2, interpreted as small (>0.01), medium (>0.06), and large (>0.14) (Tomczak and Tomczak, 2014).

Agreement between the PVM and the IMM was evaluated using Bland-Altman analysis, reporting 95% limits of agreement (bias ± 1.96 × SD_diff) (Ludbrook, 2010). Outliers were excluded following the Tukey's method (Tukey, 1977). The acceptable bias criteria included: a) CV < 10% (Cormack et al., 2008), b) ICC (2, 1) ≥ 0.75 (Koo and Li, 2016), c) absence of fixed bias (one-sample *t*-test, $p > 0.008$), d) absence of proportional bias (no significant regression between mean and difference, $p > 0.05$), and e) absence of heteroscedasticity (White's test, $p > 0.05$). Fixed bias was assessed by calculating the mean difference between the two methods, where a non-zero mean difference would indicate a systematic offset between methods. Proportional bias was evaluated by examining the relationship between the differences and the means of the two methods using regression analysis; a significant slope would suggest that the magnitude of the difference varied according to the size of the measured value. Heteroscedasticity was assessed by inspecting the scatter of the differences relative to the magnitude of the measurements, with increasing variability indicating heteroscedasticity.

Results

The within-subject reliability of the velocities showed ICC ≥0.75 and CV <10% for both methods (Table 1). The paired *t*-tests revealed significant differences between take-off velocity and peak velocity, as well as between PVM- and IMM- derived jump heights across all conditions ($p < 0.001$). The effect sizes varied from medium to large ($g = 0.61–1.82$) (Table 2). Additionally, significant differences were observed in all force-velocity profile variables measured by the PVM and the IMM, with the PVM demonstrating higher values ($p < 0.001$). The effect sizes were large ($g = 1.00–10.81$) (Table 2).

The mean differences in PVM and IMM jump heights across the six conditions were analyzed using a one-way repeated measures ANOVA. A significant difference was identified between the BM and BM + 32 kg, 1.6 BM, and 1.8 BM conditions, with loaded conditions yielding higher values ($p < 0.01$, partial $\eta^2 = 0.32$) (Figure 1). However, no significant differences in the degree of overestimation were observed among the loaded conditions (BM + 32 kg, 1.6 BM, 1.8 BM, 2.0 BM, and 2.2 BM).

Figures 2 and 3 show Bland-Altman plots comparing jump heights and force-velocity profiles between the PVM and the IMM. Figure 2 illustrates the fixed bias of jump heights and proportional bias under the BM condition, while Figure 3 highlights not only fixed bias, but also proportional bias in F0 and FVimb. The results of tests for fixed bias, proportional bias, and heteroscedasticity are summarized in Table 3. A one-sample *t*-test indicated significant differences across all variables between the PVM and the IMM, confirming the presence of fixed bias ($p < 0.01$). Under the BM condition, F0/kg, and FVimb, the regression coefficient *p*-values were significant, suggesting proportional bias ($p < 0.05$). No heteroscedasticity was observed for any variable.

Table 1. The within-subject reliability of peak velocity and take-off velocity during the jump.

	Peak velocity				Take-off velocity			
Load (kg)	ICC (95%CI)		CV (%)		ICC (95%CI)		CV (%)	
BM	0.96	(0.85 to 0.99)	1.2	(1.0)	0.96	(0.87 to 0.99)	1.4	(1.0)
BM + 32kg	0.93	(0.75 to 0.98)	1.6	(1.2)	0.91	(0.68 to 0.98)	2.2	(2.0)
1.6 BM	0.99	(0.97 to 1.00)	1.4	(0.9)	0.94	(0.77 to 0.98)	2.3	(1.8)
1.8 BM	0.95	(0.82 to 0.99)	1.7	(1.1)	0.92	(0.73 to 0.98)	2.7	(2.4)
2.0 BM	0.93	(0.77 to 0.98)	1.6	(1.2)	0.92	(0.72 to 0.98)	2.8	(2.7)
2.2 BM	0.93	(0.75 to 0.98)	0.9	(0.6)	0.89	(0.64 to 0.97)	4.7	(5.0)

BM: body mass, ICC: intraclass correlation coefficient, CI: confidence interval, CV: coefficient of variation

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Table 2. Comparison of variables by the peak velocity method and the impulse-momentum method.

%BM	Peak velocity (m/s)		Take-off velocity (m/s)		PVM jump height (m)		IMM jump height (m)		PVM		IMM		*p* value	Hedges' *g*
BM	2.72	(0.19)	2.59	(0.22)									< 0.001	0.61
BM + 32 kg	2.14	(0.14)	1.94	(0.17)									< 0.001	1.26
1.6 BM	1.95	(0.13)	1.71	(0.17)									< 0.001	1.50
1.8 BM	1.82	(0.13)	1.56	(0.17)									< 0.001	1.57
2.0 BM	1.65	(0.12)	1.36	(0.18)									< 0.001	1.80
2.2 BM	1.52	(0.14)	1.19	(0.20)									< 0.001	1.81
BM					0.380	(0.054)	0.344	(0.058)					< 0.001	0.61
BM + 32 kg					0.235	(0.031)	0.192	(0.034)					< 0.001	1.26
1.6 BM					0.194	(0.026)	0.150	(0.030)					< 0.001	1.52
1.8 BM					0.169	(0.024)	0.126	(0.027)					< 0.001	1.59
2.0 BM					0.139	(0.021)	0.096	(0.025)					< 0.001	1.82
2.2 BM					0.119	(0.022)	0.075	(0.026)					< 0.001	1.77
F0/kg (N/kg)									52.21	(5.08)	30.96	(2.13)	< 0.001	5.22
V0 (m/s)									5.65	(0.69)	2.84	(0.36)	< 0.001	4.88
Pmax/kg (W/kg)									72.73	(5.23)	22.05	(3.60)	< 0.001	10.81
Sfv/kg									−9.49	(1.58)	−11.05	(1.40)	< 0.001	1.00
FVimb (%)									111.35	(18.94)	83.81	(11.16)	< 0.001	1.70

BM: Body mass, PVM: peak velocity estimation method, IMM: impulse momentum method, F0: theoretical maximum force, V0: theoretical maximum velocity, P_{max}: maximum power, Sfv: slope of the force-velocity profile, Fvimb: imbalance of the force-velocity profile

Table 3. Bias assessment between the peak velocity method and the impulse-momentum method.

		ICC (95%CI)				CV (%)		Fixed Bias (One-sample *t*-test's *p*)	Proportional Bias (Regression coefficient's *p*)	Heteroscedasticity (White test's *p*)
Jump Height	BM	0.82	(−0.01	to	0.97)	7.3	(2.5)	< 0.001	0.02	0.53
	BM + 32 kg	0.52	(−0.02	to	0.88)	14.6	(4.4)	< 0.001	0.16	0.61
	1.6 BM	0.41	(−0.03	to	0.83)	18.8	(6.6)	< 0.001	0.12	0.46
	1.8 BM	0.40	(−0.02	to	0.82)	21.3	(6.9)	< 0.001	0.16	0.16
	2.0 BM	0.32	(−0.02	to	0.77)	27.5	(9.8)	< 0.001	0.07	0.37
	2.2 BM	0.32	(−0.03	to	0.77)	34.4	(14.0)	< 0.001	0.42	0.57
F0/kg		0.02	(−0.02	to	0.16)	35.9	(6.1)	< 0.001	0.01	0.66
V0		0.04	(−0.01	to	0.25)	46.7	(5.2)	< 0.001	0.56	0.30
P_{max}		0.01	(−0.00	to	0.09)	76.0	(5.3)	< 0.001	0.06	0.30
Sfv		0.48	(−0.012	to	0.85)	−11.3	(8.1)	< 0.001	0.63	0.97
FVimb		0.26	(−0.08	to	0.70)	19.5	(7.7)	< 0.001	0.046	0.35

ICC: intraclass correlation coefficient, CI: confidence interval, CV: coefficient of variation, BM: body mass, F0: theoretical maximum force, V0: theoretical maximum velocity, P_{max}: maximum power, Sfv: slope of the force-velocity profile, Fvimb: imbalance of the force-velocity profile

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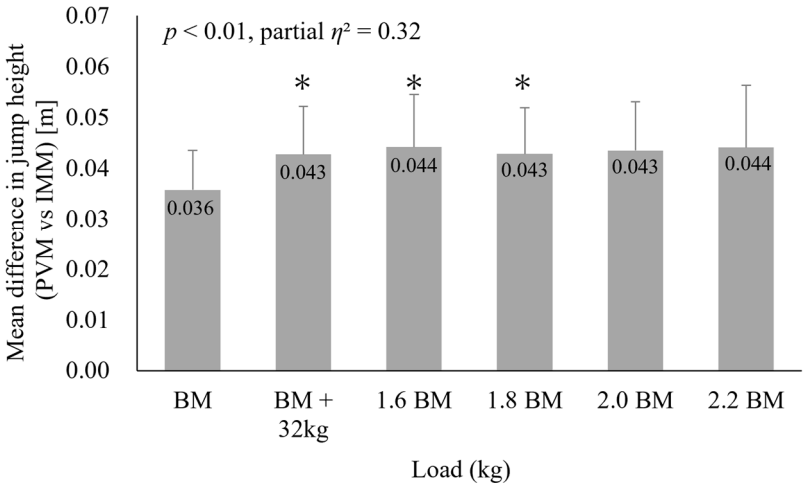


Figure 1. Comparison of the mean differences between the peak velocity method and the impulse-momentum method across conditions.

*BM: Body mass, PVM: peak velocity estimation method, IMM: impulse momentum method, *: significant difference from the BM condition ($p < 0.05$)*

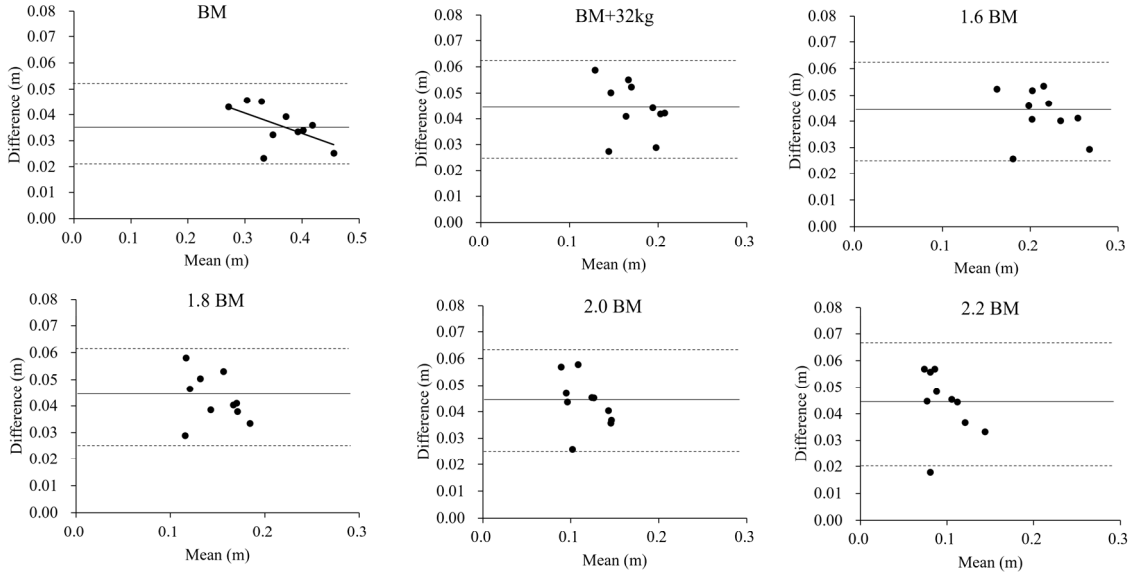


Figure 2. Bland-Altman plot comparing jump heights from the peak velocity and impulse-momentum methods.

BM: Body mass

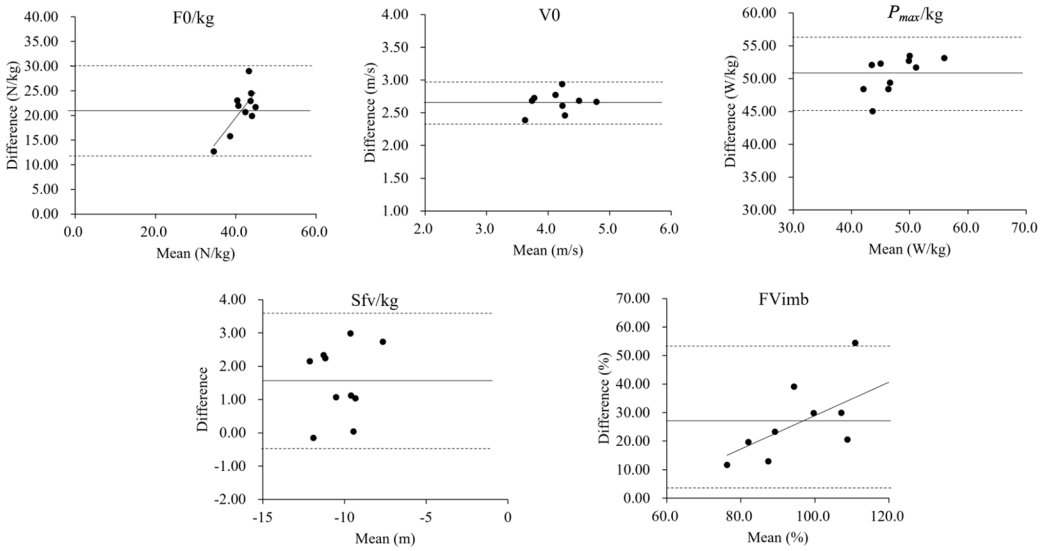


Figure 3. Bland-Altman plot comparing the force-velocity profile between the peak velocity and impulse-momentum methods.

F0: theoretical maximum force, V0: theoretical maximum velocity, P_{max}: maximum power, Sfv: slope of the force-velocity profile, Fvimb: imbalance of the force-velocity profile

Discussion

The purpose of this study was to validate the accuracy of the PVM while excluding factors related to device differences. Additionally, the validity of the force-velocity (F-V) profile using the PVM was examined. The results showed that the PVM overestimated jump height and the force-velocity profile compared to the IMM, and that the degree of jump height overestimation was greater under loaded conditions (BM + 32 kg, 1.6 BM, and 1.8 BM) than under the BM condition. These findings were consistent with our hypothesis. Contrary to our initial hypothesis, there were no differences in the degree of overestimation among the loaded conditions (BM + 32 kg and 1.6, 1.8, 2.0, and 2.2 BM). Furthermore, a proportional bias was observed under the BM condition, F0/kg, and FVimb.

In terms of jump height, the PVM consistently exhibited significantly higher values than the IMM under all conditions. Even under the BM condition, where the CV and ICC values were within acceptable ranges, a fixed bias was observed across all conditions. This indicates that the PVM overestimates jump height compared to the IMM, suggesting lower validity. Rantalainen et al. (2018) used a PVM with inertial measurement units and reported an average overestimation of 9.4 cm. In the present study, the PVM overestimated jump height by an average of 3.6 cm compared to the IMM under the BM condition, suggesting a difference in the degree of overestimation. Since in the present study the peak and take-off velocities of the center of mass were derived from the same ground reaction forces obtained via a force plate, device-dependent errors were excluded. Therefore, the difference in overestimation compared to the study by Rantalainen et al. (2018) might be partially explained by device-dependent factors, such as the presence of signal noise, differences in filtering procedures, and the inherent precision of the device itself. The degree of overestimation found in this study can be considered valid for the PVM

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itself. However, since no direct comparison across devices was conducted in the present study, this remains speculative and should be interpreted with caution. Although it is mechanically predictable that the PVM yields higher values than the IMM, the present study quantified the extent of this overestimation and found medium effect sizes (Hedges' g = 0.61). Furthermore, using the Bland-Altman 95% LoA technique, the overestimation was estimated to range from 2.1 to 5.1 cm. Importantly, a proportional bias was observed only for the BM condition in this study. This indicates that simply applying a uniform correction of 3.6 cm was insufficient. The observed negative slope suggests that the error decreased as the jump height increased. The peak velocity of the center of mass during a jump occurs immediately before the take-off, and take-off velocity is generally lower than peak velocity (Cormie et al., 2008). This discrepancy likely arises because the toes cannot apply sufficient force to the ground to accelerate the center of mass upward just before the take-off, resulting in slight deceleration. In fact, at the moment of the take-off, it is necessary to reduce the ground reaction force through values lower than body weight to zero, and thus, a decrease in velocity from the peak to the take-off is considered a physically inevitable phenomenon. Additionally, we observed a tendency for the error to decrease as jump height increased. This may be related to a greater ability to generate force during the latter part of the upward phase of the jump. If higher force is produced during the latter phase, the difference between peak velocity and take-off velocity may become smaller, thereby reducing the overestimation by the PVM. In fact, Nishiumi and Hirose (2024a) showed that mean force during the latter part of the upward phase was more strongly associated with jump height (r = 0.83) than mean force during the early phase (r = 0.51). In practical sports, considering both device-dependent errors and the proportional bias observed in this study, the PVM cannot be deemed a valid method for measuring jump height and is therefore not recommended.

On the other hand, the loaded conditions resulted in a greater overestimation compared with the BM condition. As the load increases, it becomes more difficult to push off the ground with the toes immediately before the take-off, leading to a discrepancy between peak and take-off velocities. In fact, some studies have suggested that toe strength is associated with jump height (Yamauchi and Koyama, 2020). Improving toe strength and force generation capacity may help minimize deceleration from peak velocity to take-off velocity during a loaded jump. Interestingly, the degree of overestimation increased from the BM condition to loaded conditions, although no further increase was observed among the loaded conditions themselves (i.e., among 32 kg, 1.6 BM, 1.8 BM, 2.0 BM, and 2.2 BM). When handling weights of at least 32 kg (approximately 1.42 BM for the participants in this study), jump height was consistently overestimated by an average of 4.3 to 4.4 cm, with a range of approximately 2.0 cm to 6.8 cm, as determined by the Bland-Altman 95% LoA technique. These findings may suggest a plateau in the magnitude of overestimation beyond a certain loading threshold. Future studies should investigate the load threshold relative to BM at which the degree of overestimation changes. On the other hand, although the differences in overestimation errors between the BM CMJ and loaded jumps were associated with large effect sizes (partial $\eta^2 > 0.14$), the actual magnitude of the differences was approximately 1 cm. Therefore, when focusing solely on the numerical discrepancy, the practical relevance of this difference may be limited in strength and conditioning practice or athlete monitoring contexts.

For variables in the force-velocity profile, the PVM consistently showed significantly higher values for all variables, with large CVs, low ICCs, and the presence of both fixed and proportional biases across all variables. The characteristics of F0 and V0 were derived by plotting the average ground reaction force and the average center of mass velocity during each jump on a scatter plot, where the intersection of the regression line with the y- and x-axes provided F0 and V0, respectively (Samozino et al., 2012). However, this method amplifies small measurement errors, resulting in significant inaccuracies. In this study, the overestimated jump heights measured by the PVM were used to calculate the average ground reaction force and the center of mass velocity, which were then plotted to obtain F0 and V0 from the regression equation, likely resulting in even greater errors. Furthermore, P_{max}, calculated as the product of F0 and V0 divided by 4 (Samozino et al.,

2012), may have compounded these errors, leading to substantial inaccuracies. Previous research has recommended that the CV of jump heights should be less than 5% when determining the force-velocity profile (Samozino et al., 2022), but the results of this study significantly deviated from this standard. In addition, F0 and FVimb exhibited fixed and proportional biases in the positive direction. One possible reason for this positive bias is the greater overestimation of jump heights under loaded conditions than under BM conditions. In this study, the BM condition was the closest to V0, whereas the loaded conditions were closer to F0, making each condition more likely to affect V0 and F0. Consequently, a greater overestimation under loaded conditions may have caused F0 to be overestimated more than V0, leading to positively biased errors in Sfv and FVimb. This issue could undermine the primary purpose of measuring the force-velocity profile to design individualized training. A previous study demonstrated the effectiveness of individualized training by categorizing individuals into FVimb < 90% and FVimb > 110% (Jiménez-Reyes et al., 2017). In this study, while the FVimb for the IMM averaged 83.9%, indicating that many participants were in the FVimb < 90% category, the FVimb for the PVM averaged 111.3%, leading to misclassification into the FVimb > 110% category. These findings indicate that measuring the force-velocity profile using the PVM is not valid. If an athlete with an FVimb < 90% profile is misclassified as having an FVimb > 110%, they may be prescribed low-load, velocity-oriented jump training instead of heavy resistance training that would be more appropriate for their actual profile. This mismatch could hinder performance gains, as low-load, high-speed training is unlikely to sufficiently improve maximum force output. Therefore, FV profiling based on inaccurate measurements like those from the PVM may undermine the core rationale behind individualized training strategies. However, recent studies have raised critical questions regarding the theoretical basis and practical utility of force-velocity profiling (Bobbert et al., 2023; Lindberg et al., 2021). Our findings similarly indicate that measurement errors associated with the peak velocity method (PVM) could lead to incorrect individual classifications based on FVimb. Therefore, caution is warranted when using the force-velocity profile for training prescription and athlete evaluation, and practitioners should carefully consider both its theoretical limitations and its susceptibility to measurement errors.

The limitations of this study include the absence of measurements using loads between BM and 32 kg, as well as loads greater than 2.2 BM. As mentioned earlier, it remains unclear at what weight below 32 kg the extent of overestimation changes, as well as the degree of overestimation at weights exceeding 2.2 BM. Future research should investigate the threshold load at which overestimation by the PVM begins to significantly increase compared to the BM condition, as well as the magnitude of error at loads exceeding 2.2 BM. It would also be beneficial to determine whether this threshold varies depending on individual characteristics such as body mass or jump strategy. Additionally, a minimum load of 32 kg was used in this study, which may be relatively heavy for lighter athletes. As such, the applicability of our findings to populations requiring lower external loading (e.g., youth or female athletes) may be limited. The other potential limitation of this study is the determination of the take-off using a 20-N threshold for vertical ground reaction force. Although this approach is commonly used in jump analyses (Harry et al., 2020; Nishiumi et al., 2023), the selection of the threshold can influence the identification of take-off timing and, consequently, the calculation of take-off velocity. Additionally, the use of a 50-Hz low-pass filter may have affected the determination of take-off velocity, potentially introducing a slight error in the calculation of jump height. Future studies may benefit from evaluating the sensitivity of outcomes to different threshold values and filter settings. In this study, the measurements were conducted under loaded conditions using a Smith machine. Since free weights involve instability in both the anteroposterior and lateral directions, the potential for greater errors is higher. Furthermore, while the PVM is relatively inexpensive and commonly used in inertial measurement units, it demonstrates not only a fixed bias, but also a proportional bias under BM conditions. Considering that equipment-dependent errors are also included, the use of the PVM is not recommended.

In conclusion, the findings of this study demonstrate that the PVM consistently overestimates both jump height and force-velocity

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profile variables compared with the IMM. Proportional bias was observed in BM as well as in F0/kg and FVimb. Furthermore, the loaded conditions (BM + 32 kg, 1.6 BM, and 1.8 BM) resulted in a greater overestimation of jump height than the BM condition. These results indicate that the PVM introduces significant errors, including fixed and proportional biases, and is not valid for measuring jump height or constructing force-velocity profiles. These errors undermine the reliability of the PVM in applications that require accurate force-velocity profiling and individualized training prescriptions. This study highlights the need for alternative methods to ensure accurate assessment in sports and athletic contexts.

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