European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads

Danica Janicijevic, Olivera Knezevic, Dragan Mirkov, Alejandro Pérez-Castilla, Milos Petrovic, Pierre Samozino & Amador Garcia-Ramos

Publisher: Taylor & Francis & European College of Sport Science
Journal: *European Journal of Sport Science*
DOI: 10.1080/17461391.2019.1645886

Check for updates

Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads

Running title: Assessment of the F-V relationship during the SJ

Word count of the manuscript: 3997

Authors: Danica Janicijevic,[1] Olivera Knezevic,[2] Dragan Mirkov,[1] Alejandro Pérez-Castilla,[3] Milos Petrovic,[1] Pierre Samozino,[4] Amador Garcia-Ramos[3,5]

Institutional Affiliations:
[1] University of Belgrade, Faculty of Sport and Physical Education, The Research Centre, Belgrade, Serbia.
[2] University of Belgrade, Institute for Medical Research, Belgrade, Serbia.
[3] University of Granada, Faculty of Sport Sciences, Department of Physical Education and Sport, Granada, Spain.
[4] Univ Savoie Mont Blanc, Laboratoire Interuniversitaire de Biologie de la Motricité, EA 7424, F-73000 Chambéry, France.
[5] Universidad Católica de la Santísima Concepción, Faculty of Education, Department of Sports Sciences and Physical Conditioning, Concepción, Chile.

Corresponding author:
Amador García-Ramos. Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Granada, Spain. Department of Sports Sciences and Physical Conditioning, Faculty of Education, Universidad Católica de la Santísima Concepción, Concepción, Chile. Tel.: +34677815348. E-mail: amagr@ugr.es

Acknowledgments
The present study was conducted under the supervision of Prof. Slobodan Jaric, who passed away during the writing process of this paper. We wish to thank Prof. Slobodan Jaric for inspiring our past, present and future research work. We would also like to thank Prof. Jean-Benoit Morin for his constructive comments that have contributed to improve the quality of the manuscript. This work was partially supported by the grants 175037 and 175012 from the Ministry of education, science and technological development of Republic of Serbia, by the University of Granada under a post-doctoral grant (perfeccionamiento de doctores) awarded to AGR, and by the Spanish Ministry of Education, Culture and Sport under a pre-doctoral grant (FPU15/03649) awarded to APC.

Assessment of the force-velocity relationship during vertical jumps: influence of the starting position, analysis procedures and number of loads

Abstract

This study aimed to compare the reliability and magnitude of the force-velocity (F-V) relationship parameters between the squat jumps performed from the 90º (SJ90) and self-preferred knee angle (SJ_{pref}). A secondary aim was to explore the effect of the analysis procedure (force platform [FP] and Samozino's [SAM] method) and the number of loads tested (three- and two-point methods) on the F-V relationships. Twelve men were tested in two sessions during the SJ90 and SJ_{pref}. Two identical blocks of jumps were performed in each session against three external loads. The F-V relationship parameters (maximum force, maximum velocity, F-V slope and maximum power) were determined at each block through the FP and SAM procedures using the data collected under three (three-point method) or only the two most distant loads (two-point method). The average coefficient of variation (CV) of the four F-V parameters revealed a higher reliability for the SJ90 compared to the SJ_{pref} (5.86% *vs.* 7.55%; CV_{ratio}=1.29) with more pronounced differences using the FP (CV_{ratio}=1.43) than the SAM procedure (CV_{ratio}=1.14), and higher reliability for the SAM compared to the FP (6.14% *vs.* 7.27%; CV_{ratio}=1.18). The SJ_{pref} and SAM procedures provided comparable or higher magnitude of the F-V relationship parameters than the SJ90 and FP, respectively. The three- and two-point methods revealed a comparable reliability and trivial differences in the magnitude of the F-V relationship parameters. The routine testing procedure of the F-V relationship could be simplified using the SJ_{pref}, the SAM procedure and the two-point method.

Keywords: force platform, Samozino's method, multiple-point method, two-point method.

Introduction

Vertical jumps are widely used for assessing the function of lower-body muscles (Claudino et al., 2017). Vertical jumps are frequently performed against external loads to obtain a more comprehensive examination of muscle function (Cuk et al., 2014; Samozino et al., 2014). The recording of force and velocity outputs under several loads allows to determine the force-velocity (F-V) relationship through a linear regression model (Jaric, 2015). The outcomes of the F-V relationship (maximum force [F_0], maximum velocity [V_0], and maximum power [Pmax]) provide more meaningful information than the values of force, velocity and power collected under individual loads (Jaric, 2015). However, it is still necessary to refine the testing procedure of the F-V relationship during vertical jumps, being the standardization of the starting position (Petronijevic et al., 2018), the analysis procedure (Giroux, Rabita, Chollet, & Guilhem, 2014), or the number of external loads (Garcia-Ramos, Pérez-Castilla, & Jaric, 2018) some of the issues that require further investigation.

The force platform (FP) is considered as the "gold-standard" for assessing the F-V relationship during vertical jumps (Cuk et al., 2014). However, since the FP is limited to laboratory conditions, Samozino and colleagues proposed a simple method (named Samozino's [SAM] method) to estimate the mean values of force and velocity from three input variables (system mass, jump height and push-off distance) (Samozino, Morin, Hintzy, & Belli, 2008). A high concurrent validity of the SAM method with respect to the FP method has been reported for the mean values of force and velocity collected under individual loads as well as for the outcomes of the F-V relationship (Giroux et al., 2014; Jímenez-Reyes et al., 2017). In addition, Giroux et al. (2014) suggested that the SAM method could provide force and velocity outputs under individual loads with comparable reliability than a FP. However, no previous study has compared the reliability of the outcomes of the F-V relationship between the FP and SAM methods.

The standard testing procedure used to evaluate the F-V relationship consists of performing vertical jumps against more than two external loads (Giroux, Rabita, Chollet, & Guilhem, 2016; Jiménez-Reyes, Samozino, Brughelli, & Morin, 2017; Pérez-Castilla, García-Ramos, Padial, Morales-Artacho, & Feriche, 2018). However, under the assumption that the F-V relationship of multi-joint tasks is highly linear, Jaric (2016) suggested that the F-V relationship could be accurately determined from the force and velocity data recorded under only two different loads. In this regard, Garcia-Ramos et al. (2018a) reported that the outcomes of the F-V relationship during both the squat jump (SJ) and countermovement jump exercises can be obtained with comparable reliability from a two-point method based on distant loads compared to the standard multiple-point method. However, the reliability and validity of the two-point method for testing the F-V relationship during vertical jumps have never been explored under field conditions (i.e., applying only two loads during the testing procedure). Therefore, it would be important to assess the reliability of the two-point method under field conditions as well as to elucidate whether the addition of an intermediate load (i.e., three-point method) could enhance the reliability of the F-V relationship.

One of the most important problems regarding the evaluation of vertical jumps is how to standardise the starting position (e.g., knee angle). Specifically, there is controversy regarding whether the most standard 90º knee angle or the self-preferred knee angle should be recommended (Argus & Chapman, 2014; Domire & Challis, 2007; Mitchell, Argus, Taylor, Sheppard, & Chapman, 2017; Petronijevic et al., 2018). It is already known that the self-preferred knee angle is between 90 and 100º (Mitchell et al., 2017; Petronijevic et al., 2018). It is also known that the increment of the knee angle from 90 to 100º is associated with higher force outputs, while velocity and jump height values remain practically stable (Argus & Chapman, 2014; La Torre et al., 2010; Mitchell et al., 2017). Therefore, it would be of practical interest to evaluate the effect of the starting position (90º knee angle *vs.* self-preferred knee angle) on the reliability and magnitude of the F-V relationship parameters.

To address the existing gaps in the literature, the F-V relationship during the SJ exercise performed from the standard 90º knee angle (SJ90) and from the self-preferred knee angle (SJ_{pref}) was assessed in the present study. The main aim of the present study was to compare the reliability and magnitude of the F-V relationship parameters between the SJ90 and SJ_{pref}. A secondary aim was to explore the effect of the analysis procedure (FP and SAM) and the number of loads tested (three- and two-point methods) on the F-V relationships. We hypothesised that (I) the magnitude of the F-V relationship parameters would be higher for the SJ_{pref} (Gheller et al., 2015), while the lack of similar studies did not allow us to hypothesise about their differences in reliability, (II) no systematic bias and high correlations would be observed for the magnitude of the same F-V relationship parameters between the FP and SAM methods, while the SAM method would provide more reliable outcomes (Giroux et al., 2014; Jímenez-Reyes et al., 2017), and (III) no significant differences would be observed neither in the magnitude nor in the reliability of the F-V relationship parameters between the three- and two-point methods, while their outcomes would be highly correlated (Garcia-Ramos, Pérez-Castilla, et al., 2018).

Methods

Participants

Twelve male sports science students participated in this study (mean ± standard deviation [SD]: age: 22.7 ± 2.8 years; body mass: 79.6 ± 8.7 kg; height: 1.82 ± 0.08 m). All participants were physically active through their academic curriculum, which included approximately eight physical activity classes per week. Prior to testing, participants were informed about research purpose and procedures, and they gave their written consent to participate in the study. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board.

Design

A randomised crossover design was used to investigate the effect of the knee angle (SJ90 *vs.* SJ_{pref}) on the F-V relationship assessed through the FP and SAM procedures during the SJ exercise. After a familiarization session that was also used to determine the external load associated with a jump height of ≈ 10 cm, participants were tested in two sessions separated by at least 48 hours. A single SJ type was evaluated on each testing session. Two identical blocks of jumps were performed during each session separated by 5 min. Each block comprised six vertical jumps that were performed in the following order: two SJ with a plastic barbell of 0.5 kg, two SJ with a load that allowed a jump height of ≈ 10 cm (61.4 ± 12.4 kg), and two SJ with a load that represented half the weight of the heaviest load (31.0 ± 6.3 kg).

Testing procedures

All sessions began with a standardised warm-up consisting of 10 min of cycling and joint mobility exercises, followed by three, two and one SJ trials with the light, medium and heavy loads, respectively. Subsequently, two blocks of jumps were performed in the following order: two SJ with the light load, two SJ with the heavy load, and two SJ with the medium load. The rest periods between trials with the same load, trials of different loading conditions within the block, and trials of different blocks were set to 1, 3, and 5 minutes, respectively. All jumps were performed with a free-weight barbell. Two SJ types were tested:

- *SJ90*: Participants were required to maintain a static squat position with 90º of knee flexion for 2 seconds, and afterwards they performed the concentric phase with the instruction of jumping as high as possible. The knee angle was monitored by means of a manual goniometer, and an elastic cord was individually adjusted to contact with the participants' buttocks when they reached the 90º knee angle.

- *SJ_{pref}*: Participants self-selected the starting position (knee angle = 92.3 ± 11.1º) that was thereafter maintained for 2 seconds, and then they performed the concentric phase with the instruction of jumping as high as possible. Participants were instructed to maintain a similar starting position during all trials, but no reference was used to standardise the starting position.

Measurement equipment and data analysis

- *Force plate (FP) procedure*: All SJs were performed on a force platform (AMTI BP600400, Advanced Mechanical Technology, Inc. Watertown, MA 02472-4800 USA) that sampled the vertical component of the ground reaction force at 1,000 Hz. The initiation of the concentric phase was defined as the first instance when ground reaction force was 20 N above the system weight and the take-off was identified as the instant when the ground reaction force fell below 10 N.

- *Samozino's (SAM) procedure*: The mean values of force and velocity were calculated from the equations proposed by Samozino et al. (2008). Jump height was estimated from flight time using a validated mobile application (MyJump2) that recorded the video-image at 240 fps through an iPhone 8 plus (Balsalobre-Fernandez, Glaister, & Lockey, 2015). The push-off distance was determined as the difference between the extended lower limb length (measured from the great trochanter to tip of the toes with maximal foot plantar flexion) and the vertical distance between the great trochanter and the ground with knees flexed at 90º (SJ90) or at the self-preferred knee angle measured with the medium load (SJ_{pref}). The push-off distance value was kept constant for the computations during all trials performed with the same SJ type.

Only the trial with the highest jump height of each load measured with MyJump2 was used for further analysis. The mean values of force and velocity obtained under three (three-point method) or two (two-point method) 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 represents the force intercept and a is the slope of the F-V relationship. The maximum velocity (V_0) corresponds to F_0/a. Finally, maximum power (Pmax) was calculated as Pmax = $F_0 \cdot V_0/4$.

Statistical analyses

Descriptive data of the F-V relationship parameters are presented as means and SD, while the Pearson's correlation coefficients (r) are presented through their median value and range. Reliability was assessed by the coefficient of variation ($\text{CV}\,(\%) = \frac{\text{Standard error of measurement}}{\text{Participants' mean score}} \times 100$), the intraclass correlation coefficient (ICC; model 3.1), and the 95% confidence interval (CI). Acceptable reliability was determined as a CV < 10% and practical differences in reliability were identified as a CV_{ratio} > 1.15 (Fulton, Pyne, Hopkins, & Burkett, 2009; Petronijevic et al., 2018). A three-way repeated measures ANOVA (SJ type [SJ90 and SJ_{pref}], procedure [FP and SAM] and method [three- and two-point methods]) with Bonferroni post hoc tests was applied on each F-V relationship parameter. The magnitude of the differences was quantified through the raw mean differences, Cohen's d effect size (ES; calculated as the raw mean difference divided by the pooled SD of the compared conditions), and their respective 95% CI. The following scale was used to interpret the magnitude of the ES: trivial (< 0.2), small (0.2-0.59), moderate (0.60-1.19), large (1.2-2.0) and very large (> 2.0) (Hopkins, Marshall, Batterham, & Hanin, 2009). The r coefficient was used to explore the association of the F-V relationship parameters between the compared conditions. The criteria for interpreting the magnitude of the r coefficients were: *trivial* (0.00–0.09), *small* (0.10–0.29), *moderate* (0.30–0.49), *large* (0.50–0.69), *very large* (0.70–0.89), *nearly perfect* (0.90–0.99) and *perfect* (1.00) (Hopkins et al., 2009). The data of the two blocks were used for reliability analyses, while only the first block was used for the remaining analyses. The reliability analysis was performed by means of a custom Excel spreadsheets (Hopkins, 2000), while other statistical analyses were performed using the software package SPSS (IBM SPSS version 22.0, Chicago, IL, USA).

Results

The averaged across the participants ($r \geq 0.99$; Figure 1) and individual F-V relationships modelled through the three-point method were highly linear (FP SJ90 = 0.988 [0.877-1.000], FP SJ_{pref} = 0.993 [0.892-1.000], SAM SJ90 = 0.997 [0.963-0.999], and SAM SJ_{pref} = 0.995 [0.932-1.000]).

[Figure 1]

Acceptable reliability was observed for F_0 (CV = 4.30 [range: 2.87-5.78%]), V_0 (CV = 7.77 [range: 6.08-9.96%]) and Pmax (CV = 3.74 [range: 3.24-4.22%]), while the F-V slope did not meet the criteria of acceptable reliability in 5 out of 8 comparisons (CV = 11.02 [range: 8.42-14.68%]) (Table 1). When considering the average CV value of the four F-V relationship parameters: (I) the SJ90 provided a higher reliability than the SJ_{pref} (5.86% *vs.* 7.55%; CV_{ratio} = 1.29), (II) the SAM provided a higher reliability than the FP (6.14% *vs.* 7.27%; CV_{ratio} = 1.18), and (III) the three- and two-point methods provided a comparable reliability (6.52% *vs.* 6.90%; CV_{ratio} = 1.06). The SJ90 provided a higher reliability compared to the SJ_{pref} using the FP procedure (5.99% *vs.* 8.55%; CV_{ratio} = 1.43), but no meaningful differences in reliability between the SJ types were observed using the SAM procedure (5.74% *vs.* 6.55%; CV_{ratio} = 1.14). The SAM procedure provided a higher reliability during the SJ_{pref} (CV_{ratio} = 1.31), but not during the SJ90 (CV_{ratio} = 1.04).

[Table 1]

The ANOVA revealed a significant main effect of SJ type (Pmax was significantly higher for the SJ_{pref}), procedure (V_0 and Pmax were significantly higher for SAM), and method (F_0 and the absolute values of the F-V slope were significantly higher for the two-point method, whereas V_0 and Pmax were significantly higher for three-point method) (Table 2). The only significant interactions were the SJ type × procedure (V_0 and Pmax; higher differences in favour of the SAM procedure were observed during the SJ90) and procedure × method (F_0 and F-V slope; higher differences in favour of the SAM procedure using the two-point method). The magnitude of the differences was generally trivial (27 out of 48 comparisons) or small (15 out of 48 comparisons) (Figure 2). The only moderate differences were observed for the values of V_0 and Pmax that were higher for the SAM compared to the FP procedure during the SJ90 (ES ranged from 0.72 to 0.84) and for Pmax which was larger for the SJ_{pref} compared to the SJ90 using the FP procedure (ES = 0.65).

[Table 2]

[Figure 2]

The SJ90 and SJ_{pref} presented very large correlations for Pmax (r = 0.860 [0.731-0.950]), large for F_0 (r = 0.686 [0.619-0.747]), and moderate for V_0 (r = 0.473 [0.419-0.538]) and the F-V slope (r = 0.497 [0.459-0.526]). The FP and SAM procedures presented very large correlations for F_0 (r = 0.822 [0.801-0.835]) and Pmax (r = 0.881 [0.846-0.893]) and large for V_0 (r = 0.634 [0.610-0.693]) and the F-V slope (r = 0.663 [0.604-0.721]). The three- and two-point methods always presented nearly perfect correlations (r = 0.996 [0.992-0.999]).

Discussion

This study was designed to further refine the testing procedure of the F-V relationship during the SJ exercise. The main findings related to the SJ type revealed that the reliability of the F-V relationship parameters was lower for the SJ_{pref} compared to the SJ90 using the FP but not using the SAM procedure, the magnitude of the F-V relationship parameters was comparable or higher for the SJ_{pref}, and the two SJ types presented very large correlations for Pmax, large for F_0 and moderate for V_0 and the F-V slope. When compared to the FP procedure, the SAM procedure revealed a higher reliability during the SJ_{pref} (no meaningful differences during the SJ90), higher magnitudes of V_0 and Pmax during the SJ90 (no meaningful differences for F_0 or during the SJ_{pref}), and the magnitude of the correlations was very large (F_0 and Pmax) or large (V_0 and F-V slope). The three- and two-point methods provided the F-V relationship parameters with a comparable reliability, trivial differences in their magnitudes and nearly perfect correlations.

In line with the results of this study, all previous studies conducted with vertical jumps have reported that the F-V relationship is highly linear (Cuk et al., 2014; Garcia-Ramos et al., 2017; Jiménez-Reyes et al., 2017; Pérez-Castilla et al., 2018). However, to date only three studies have explored the reliability of the F-V relationship parameters during vertical jumps and all of them used the FP procedure (Cuk et al., 2014; Garcia-Ramos, Pérez-Castilla, et al., 2018; Garcia-Ramos et al., 2017). Our results corroborated previous findings showing that F_0 and Pmax are more reliable than V_0 and the F-V slope. The higher extrapolation needed from the experimental points to the velocity-intercept could be responsible of these results (Garcia-Ramos & Jaric, 2018b). Therefore, since the reliability of V_0 and specially the F-V slope seems to be on the edge of what is acceptable (CV ≈ 10%), it is crucial to refine the testing procedures to maximise their reliability.

The SJ_{pref} could simplify the testing procedure and be more ecologically valid than the SJ90. However, a limitation of the SJ_{pref} is that the push-off distance could be more variable and this could affect the mean values of force and velocity (higher values at higher knee angles [i.e., decreased push-off distances]) (Mandic, Jakovljevic, & Jaric, 2015; Petronijevic et al., 2018). The lower reliability of the F-V relationship parameters for the SJ_{pref} compared to the SJ90 using the FP could be explained by a higher variability of the push-off distance. On the other hand, the comparable reliability of the F-V relationship parameters between both SJ types using the SAM procedure could be explained by the use of the same a-priori measured push-off distance for computations. To sum up, a fixed knee angle (e.g., SJ90) could be preferable to determine the F-V relationship with the FP procedure, while the SJ_{pref} can be confidently used to determine the F-V relationship through the SAM procedure provide that the push-off distance is kept fixed for the computations.

In line with the results of previous studies, the self-preferred knee angle was slightly higher than the standard 90º knee angle (Argus & Chapman, 2014; Domire & Challis, 2007; Mitchell et al., 2017; Petronijevic et al., 2018). Assuming that the jump height was the same for both SJ types, an increase of the knee angle (i.e., SJ_{pref}) would be associated with larger mean force values recorded by both the FP and SAM procedures, while mean velocity would be higher for the FP procedure and no meaningful differences are expected using the SAM procedure because mean velocity only depends on jump height (Samozino et al., 2008). These assumptions seem to be supported by the results of this study since F_0 (ES = 0.38-0.42) V_0 (ES = 0.34-0.38) and Pmax (ES = 0.65) were higher for the SJ_{pref} using the FP procedure, and only F_0 (ES = 0.36-0.39) and slightly Pmax (ES = 0.20-0.24) were higher for the SJ_{pref} using the SAM procedure. The higher differences in F_0 compared to V_0 between the SJ types may also be partially explained because the mechanical advantage of the SJ_{pref} could be accentuated against heavy loading conditions. Finally, it should be noted that while the correlations between the two SJ types for F_0 and Pmax were very large, only moderate correlations were observed for V_0 and the F-V slope which could be attributable to their lower reliability. These results suggest that both SJ types should not be used interchangeably during the routine testing of the F-V relationship.

The main advantage of the SAM procedure is that it enables to determine the F-V relationship in field conditions with cost-effective devices such as smartphone applications (MyJump2) (Balsalobre-Fernandez et al., 2015). However, although the SAM procedure has been extensively used in scientific research, this is the first study that has evaluated the reliability of the F-V relationship parameters. The results of the present study suggest that the SAM procedure can provide the F-V relationship parameters with a comparable reliability than the FP procedure when the knee angle is fixed (SJ90), while it can provide even a higher reliability during the SJ_{pref}. The lower reliability of the FP procedure observed during the SJ_{pref} could be explained because the mean values of force and velocity could present a higher variability when the knee angle is not strictly controlled (higher values at higher knee angles) (Mandic et al., 2015; Petronijevic et al., 2018). The high validity of the SAM procedure to determine the F-V relationship parameters previously reported was confirmed in the present study by the large to very large correlations observed between the FP and SAM procedures (Jiménez-Reyes et al., 2014). Therefore, the SAM procedure could be recommended to determine the F-V relationship due to the very high validity and the comparable, if not higher, reliability of the F-V relationship parameters in comparison with the FP procedure. However, it should be noted that the SAM procedure, especially during the SJ90, could overestimate the values of V_0 and Pmax compared to the FP procedure.

The two-point method was proposed by Jaric (2016) to simplify the testing procedure of the F-V relationship. Previous studies have confirmed that the two-point method can provide reliable and valid F-V relationship parameters in different exercises (Garcia-Ramos, Zivkovic, et al., 2018; Garcia-Ramos & Jaric, 2018a; Grbic et al., 2017), including vertical jumps (Garcia-Ramos, Pérez-Castilla, et al., 2018; Zivkovic et al., 2017). However, this is the first study that has applied the two-point method under field conditions (i.e., only two loads applied) to determine the F-V relationship during vertical jumps. The two-point method provided the F-V relationship parameters with a comparable reliability than previous studies that used six or seven loads during the testing procedures (i.e., multiple-point method) (Cuk et al., 2014; Garcia-Ramos, Pérez-Castilla, et al., 2018; Garcia-Ramos et al., 2017). It should be noted that in the present study we also tested whether the addition of an intermediate load to the two distant loads used for the two-point method could improve the reliability of the F-V relationship parameters (i.e., three-point method). Although significant differences were reached for all F-V relationship parameters between the three- and two-point methods, the trivial magnitude of the differences (ES always lower than 0.20), comparable reliability, and nearly perfect correlations support the two-point method as a quicker and less prone to fatigue method of determining the F-V relationship during vertical jumps.

A result that is worthy to be further highlighted is the nearly perfect correlations (r = 0.996 [0.992, 0.999]) observed for the same F-V relationship parameters between the three- and two-point methods. It is known that when two variables are highly correlated, small differences in their magnitude could bring statistical differences as occurred in the present study between the three- and two-point methods for 11 out of 16 comparisons despite that the magnitude of the differences was always trivial (ES < 0.15). For this reason, the practical differences were also assessed through the magnitude of the Cohen's ES (raw mean difference divided by the pooled SD of the compared conditions) and interpreted using the scale proposed by Hopkins et al. (2009). Note that although standardising the raw mean difference by the SD of the differences has also been recommended for repeated measures designs (Gibbons, Hedeker, & Davis, 1993), we used the Cohen's ES because is not affected by the level of correlation, while the calculation of the ES using the SD of the differences could provide a high ES despite that the practical differences are in fact trivial when the variables being compared are highly correlated as occurred in the present study (see supplementary file).

Conclusions

The SAM procedure provided a comparable (SJ90) or higher (SJ_{pref}) reliability than the FP procedure. While the SJ90 provided a higher reliability compared to the SJ_{pref} using the FP procedure, no practical differences in reliability were identified between both SJ types using the SAM procedure. The three- and two-point methods always revealed a comparable reliability and trivial differences in the magnitude of the F-V relationship parameters. Therefore, the testing procedure of the F-V relationship during the SJ exercise could be simplified through the SJ_{pref}, the SAM procedure and the two-point method. However, a fixed knee angle (e.g., SJ90) should be recommended when the F-V relationship is determined with the FP procedure.

References

Argus, C., & Chapman, D. W. (2014). The effect of initial knee angle on the reliability of variables derived from a squat jump. *Medicina Sportiva*, *18*(4), 125–130. https://doi.org/10.5604/17342260.1127307

Balsalobre-Fernandez, C., Glaister, M., & Lockey, R. A. (2015). The validity and reliability of an iPhone app for measuring vertical jump performance. *Journal of Sports Sciences*, *33*(15), 1574–1579. https://doi.org/10.1080/02640414.2014.996184

Claudino, J. G., Cronin, J., Mezêncio, B., McMaster, D. T., McGuigan, M., Tricoli, V., Amadio A.C., Serrão, J. C. (2017). The countermovement jump to monitor neuromuscular status: A meta-analysis. *Journal of Science and Medicine in Sport*, *20*(4), 397–402. https://doi.org/10.1016/j.jsams.2016.08.011

Cuk, I., Markovic, M., Nedeljkovic, A., Ugarkovic, D., Kukolj, M., & Jaric, S. (2014). Force-velocity relationship of leg extensors obtained from loaded and unloaded vertical jumps. *European Journal of Applied Physiology*, *114*(8), 1703–1714. https://doi.org/10.1007/s00421-014-2901-2

Domire, Z. J., & Challis, J. H. (2007). The influence of squat depth on maximal vertical jump performance. *Journal of Sports Sciences*, *25*(2), 193–200. https://doi.org/10.1080/02640410600630647

Fulton, S. K., Pyne, D., Hopkins, W., & Burkett, B. (2009). Variability and progression in competitive performance of Paralympic swimmers. *Journal of Sports Sciences*, *27*(5), 535–539. https://doi.org/10.1080/02640410802641418

García-Ramos, A., Feriche, B., Pérez-Castilla, A., Padial, P., & Jaric, S. (2017). Assessment of leg muscles mechanical capacities: Which jump, loading, and variable type provide the most reliable outcomes? *European Journal of Sport Science*, *17*(6), 690–698. https://doi.org/10.1080/17461391.2017.1304999

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

Garcia-Ramos, A., & Jaric, S. (2019). Optimization of the force-velocity relationship obtained from the bench press throw exercise: An a-posteriori multicentre reliability study. *International Journal of Sports Physiology and Performance*, *14*(3), 317–322. https://doi.org/10.1123/ijspp.2018-0457

Garcia-Ramos, A., Pérez-Castilla, A., & Jaric, S. (2018). Optimisation of applied loads when using the two-point method for assessing the force-velocity relationship during vertical jumps. *Sports Biomechanics*. 12, 1-16. https://doi.org/10.1080/14763141.2018.1545044

Garcia-Ramos, A., Zivkovic, M., Djuric, S., Majstorovic, N., Manovski, K., & Jaric, S. (2018). Assessment of the two-point method applied in field conditions for routine testing of muscle mechanical capacities in a leg cycle ergometer. *European Journal of Applied Physiology*, *118*(9), 1877–1884. https://doi.org/10.1007/s00421-018-3925-9

Gheller, R. G., Dal Pupo, J., Ache-Dias, J., Detanico, D., Padulo, J., & dos Santos, S. G. (2015). Effect of different knee starting angles on intersegmental coordination and performance in vertical jumps. *Human Movement Science*, *42*, 71–80. https://doi.org/10.1016/j.humov.2015.04.010

Gibbons, R. D., Hedeker, D. R., & Davis, J. M. (1993). Estimation of effect size from a series of experiments involving paired comparisons. *Journal of Educational Statistics*, *18*(3), 271–279. https://doi.org/10.3102/10769986018003271

Giroux, C., Rabita, G., Chollet, D., & Guilhem, G. (2014). What is the best method for assessing lower limb force-velocity relationship? *International Journal of Sports Medicine*, *36*(2), 143–149. https://doi.org/10.1055/s-0034-1385886

Giroux, Caroline, Rabita, G., Chollet, D., & Guilhem, G. (2016). Optimal balance between force and velocity differs among world-class athletes. *Journal of Applied Biomechanics*, *32*(1), 59–68. https://doi.org/10.1123/jab.2015-0070

Grbic, V., Djuric, S., Knezevic, O., Mirkov, D., Nedeljkovic, A., & Jaric, S. (2017). A novel two-velocity method for elaborate isokinetic testing of knee extensors. *International Journal of Sports Medicine*, *38*(10), 741–746. https://doi.org/10.1055/s-0043-113043

Hopkins, W. (2000). Calculations for reliability (Excel spreedsheet).

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Jaric, S. (2015). Force-velocity relationship of muscles performing multi-joint maximum performance tasks. *International Journal of Sports Medicine*, *36*(9), 699–704. https://doi.org/10.1055/s-0035-1547283

Jaric, S. (2016). Two-load method for distinguishing between muscle force, velocity, and power-producing capacities. *Sports Medicine*, *46*(11), 1585–1589. https://doi.org/10.1007/s40279-016-0531-z

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

Jiménez-Reyes, P., Samozino, P., Cuadrado-Peñafiel, V., Conceição, F., González-Badillo, J. J., & Morin, J. B. (2014). Effect of countermovement on power-force-velocity profile. *European Journal of Applied Physiology*, *114*(11), 2281–2288. https://doi.org/10.1007/s00421-014-2947-1

Jiménez-Reyes, P., Samozino, P., Pareja-Blanco, F., Conceicao, F., Cuadrado-Penafiel, V., Gonzalez-Badillo, J. J., & Morin, J.-B. (2017). Validity of a simple method for measuring force-velocity-power profile in countermovement jump. *International Journal of Sports Physiology and Performance*, *12*(1), 36–43. https://doi.org/10.1123/ijspp.2015-0484

La Torre, A., Castagna, C., Gervasoni, E., Cè, E., Rampichini, S., Ferrarin, M., & Merati, G. (2010). Acute effects of static stretching on squat jump performance at different knee starting angles. *Journal of Strength and Conditioning Research*, *24*(3), 687–694. https://doi.org/10.1519/JSC.0b013e3181c7b443

Mandic, R., Jakovljevic, S., & Jaric, S. (2015). Effects of countermovement depth on kinematic and kinetic patterns of maximum vertical jumps. *Journal of Electromyography and Kinesiology*, *25*(2), 265–272. https://doi.org/10.1016/j.jelekin.2014.11.001

Mitchell, L. J., Argus, C. K., Taylor, K. L., Sheppard, J. M., & Chapman, D. W. (2017). The effect of initial knee angle on concentric-only squat jump performance. *Research Quarterly for Exercise and Sport*, *88*(2), 184–192. https://doi.org/10.1080/02701367.2017.1293777

Pérez-Castilla, A., García-Ramos, A., Padial, P., Morales-Artacho, A. J., & Feriche, B. (2018). Effect of different velocity loss thresholds during a power-oriented resistance training program on the mechanical capacities of lower-body muscles. *Journal of Sports Sciences*, *36*(12), 1331–1339. https://doi.org/10.1080/02640414.2017.1376900

Petronijevic, M. S., García-Ramos, A., Mirkov, D. M., Jaric, S., Valdevit, Z., & Knezevic, O. M. (2018). Self-preferred initial position could be a viable alternative to the standard squat jump testing procedure. *Journal of Strength and Conditioning Research*, *32*(11), 3267–3275. https://doi.org/10.1519/jsc.0000000000002385

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

Samozino, Pierre, Morin, J. B., Hintzy, F., & Belli, A. (2008). A simple method for measuring force, velocity and power output during squat jump. *Journal of Biomechanics*, *41*(14), 2940–2945. https://doi.org/10.1016/j.jbiomech.2008.07.028

Zivkovic, M. Z., Djuric, S., Cuk, I., Suzovic, D., & Jaric, S. (2017). A simple method for assessment of muscle force, velocity, and power producing capacities from functional movement tasks. *Journal of Sports Sciences*, *35*(13), 1287–1293. https://doi.org/10.1080/02640414.2016.1221521

Figure captions

Figure 1. Force-velocity relationships obtained from the averaged across the subjects force and velocity data collected under three loads (three-point method) with a force platform (FP) and Samozino's equations (SAM) during the squat jump performed from a knee angle of 90º (SJ90) and self-preferred (SJ_{pref}). The regression equations and the corresponding Pearson's correlation coefficients (*r*) are shown. The standard deviations of the force and velocity values collected under individual loads are only presented for the FP SJ90 to improve the clarity of the figure (the magnitude of the standard deviations was similar for all force-velocity relationships). The force-velocity relationships obtained through the two-point method are not shown because they overlap.

Figure 2. Raw mean differences (95% confidence intervals) for maximum force (upper-left panel), maximum velocity (upper-right panel), force-velocity slope (lower-left panel) and maximum power (lower-right panel) between the squat jump performed from the 90º and self-preferred knee angle (Difference = SJ_{pref} – SJ90), force platform and Samozino's procedures (Difference = SAM – FP), and the three- and two-point methods (Difference = two-point method – three-point method). The *p* value obtained from a paired sample t-test, Cohen's *d*

effect size (ES) with 95% confidence interval, and Pearson's correlation coefficient (*r*) are also depicted.

Table 1. Reliability of the force-velocity relationship parameters obtained from different SJ types, procedures, and methods.

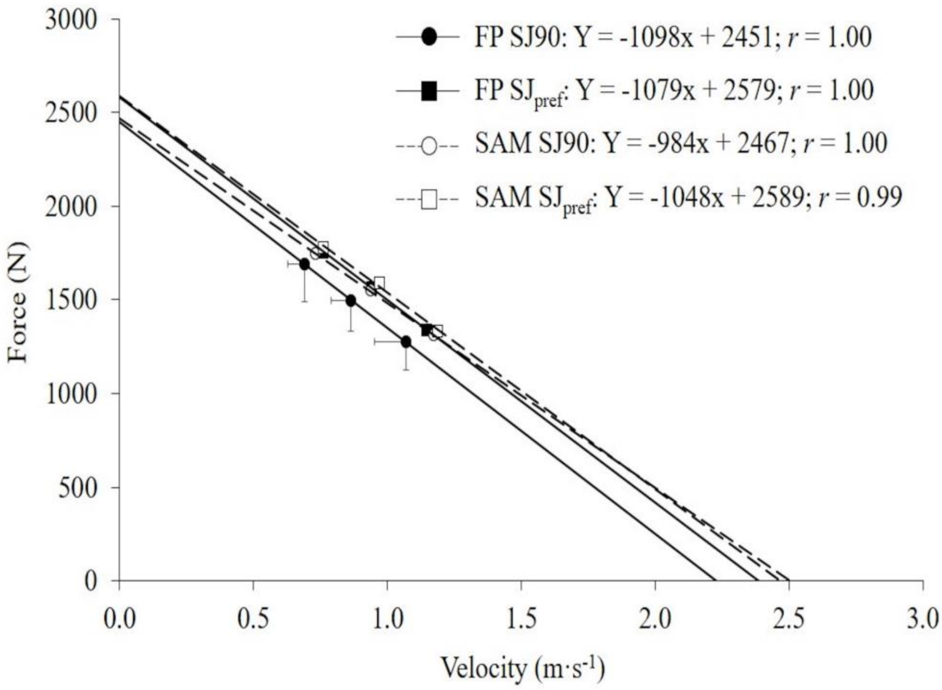
F-V parameter	SJ type	Procedure	Method	Block 1 Mean (SD)	Block 2 Mean (SD)	SEM	CV (95% CI)	ICC (95% CI)
F_0 (N)	SJ90	FP	Multiple	2452 (395)	2439 (322)	89.9	3.68 (2.60, 6.24)	0.95 (0.84, 0.99)
			Two-point	2492 (399)	2468 (321)	98.0	3.95 (2.80, 6.71)	0.94 (0.81, 0.98)
		SAM	Multiple	2488 (332)	2430 (316)	70.6	2.87 (2.04, 4.88)	0.96 (0.87, 0.99)
			Two-point	2499 (335)	2443 (318)	87.8	3.55 (2.52, 6.03)	0.94 (0.81, 0.98)
	SJ_{pref}	FP	Multiple	2630 (386)	2570 (402)	148.7	5.72 (4.05, 9.71)	0.88 (0.64, 0.96)
			Two-point	2651 (394)	2593 (408)	151.6	5.78 (4.10, 9.82)	0.88 (0.64, 0.96)
		SAM	Multiple	2574 (386)	2606 (344)	110.2	4.25 (3.01, 7.22)	0.93 (0.76, 0.98)
			Two-point	2585 (395)	2601 (346)	118.5	4.57 (3.24, 7.76)	0.92 (0.74, 0.98)
V_0 ($m \cdot s^{-1}$)	SJ90	FP	Multiple	2.31 (0.39)	2.32 (0.38)	0.161	6.98 (4.94, 11.84)	0.85 (0.57, 0.96)
			Two-point	2.24 (0.41)	2.28 (0.37)	0.164	7.23 (5.12, 12.27)	0.85 (0.57, 0.96)
		SAM	Multiple	2.54 (0.27)	2.59 (0.32)	0.156	6.08 (4.31, 10.32)	0.77 (0.37, 0.93)
			Two-point	2.53 (0.27)	2.55 (0.35)	0.190	7.47 (5.29, 12.68)	0.68 (0.20, 0.89)
	SJ_{pref}	FP	Multiple	2.37 (0.38)	2.50 (0.42)	0.242	9.93 (7.03, 16.86)	0.68 (0.20, 0.90)
			Two-point	2.33 (0.37)	2.48 (0.43)	0.240	9.96 (7.06, 16.92)	0.69 (0.21, 0.90)
		SAM	Multiple	2.57 (0.38)	2.50 (0.34)	0.177	6.99 (4.95, 11.87)	0.80 (0.44, 0.94)
			Two-point	2.53 (0.39)	2.47 (0.33)	0.188	7.51 (5.32, 12.75)	0.77 (0.38, 0.93)
F-V slope ($N \cdot s \cdot m^{-1}$)	SJ90	FP	Multiple	1104 (310)	1090 (286)	102.5	9.34 (6.62, 15.86)	0.90 (0.70, 0.97)
			Two-point	1158 (327)	1117 (290)	107.7	9.46 (6.70, 16.07)	0.90 (0.69, 0.97)
		SAM	Multiple	994 (200)	955 (204)	82.0	8.42 (5.96, 14.29)	0.86 (0.59, 0.96)
			Two-point	1003 (201)	980 (219)	103.1	10.40 (7.36, 17.65)	0.80 (0.43, 0.94)
	SJ_{pref}	FP	Multiple	1141 (282)	1060 (265)	161.6	14.68 (10.40, 24.93)	0.69 (0.23, 0.90)
			Two-point	1170 (284)	1082 (271)	158.6	14.08 (9.97, 23.91)	0.72 (0.27, 0.91)
		SAM	Multiple	1029 (240)	1065 (208)	112.4	10.74 (7.61, 18.24)	0.79 (0.43, 0.94)
			Two-point	1049 (245)	1071 (207)	117	11.04 (7.82, 18.75)	0.77 (0.39, 0.93)
Pmax (W)	SJ90	FP	Multiple	1397 (229)	1403 (253)	52.9	3.78 (2.68, 6.42)	0.96 (0.87, 0.99)
			Two-point	1382 (249)	1400 (248)	48.2	3.47 (2.46, 5.89)	0.97 (0.90, 0.99)
		SAM	Multiple	1573 (208)	1568 (240)	52.3	3.33 (2.36, 5.66)	0.96 (0.86, 0.99)
			Two-point	1573 (209)	1551 (260)	59.4	3.81 (2.70, 6.46)	0.95 (0.83, 0.99)
	SJ_{pref}	FP	Multiple	1556 (313)	1598 (302)	66.5	4.22 (2.99, 7.16)	0.96 (0.88, 0.99)
			Two-point	1540 (302)	1594 (298)	63.1	4.03 (2.85, 6.84)	0.96 (0.88, 0.99)
		SAM	Multiple	1639 (270)	1621 (268)	52.8	3.24 (2.30, 5.50)	0.97 (0.89, 0.99)
			Two-point	1623 (287)	1603 (265)	65.1	4.04 (2.86, 6.85)	0.96 (0.85, 0.99)

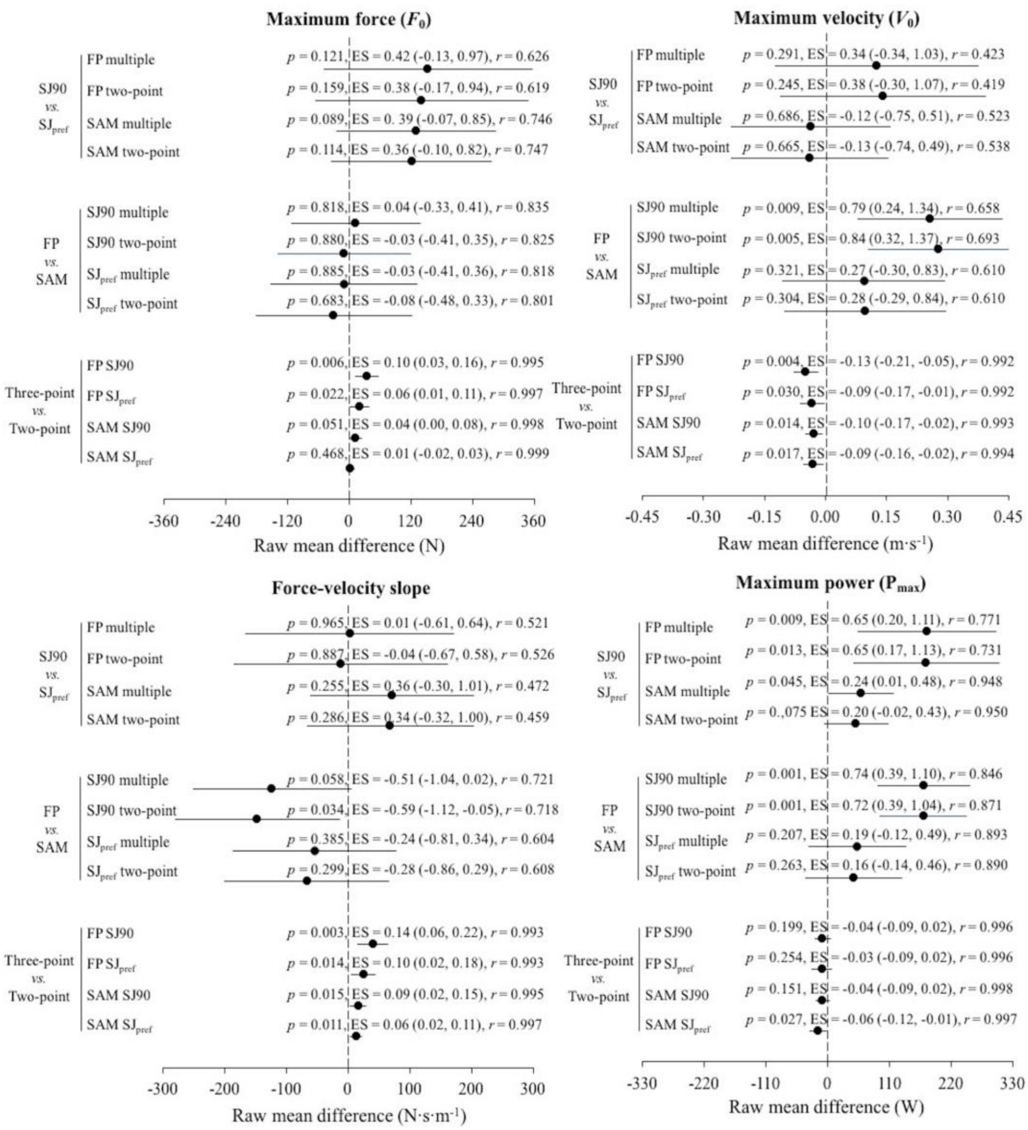
F_0, maximum force; V_0, maximum velocity, F-V slope, slope of the force-velocity relationship; Pmax, maximum power; SJ90, squat jump performed from a 90º knee angle; SJ_{pref}, squat jump performed from the self-preferred knee angle; FP, force platform; SAM, Samozino's method; SEM, standard error of the measurement; CV, coefficient of variation; ICC, intraclass correlation coefficient; CI, confidence interval. No significant differences were observed between the blocks 1 and 2 ($p > 0.05$).

Table 2. Three-way repeated measures analysis of variance (ANOVA) applied on each force-velocity relationship parameter.

	F_0	V_0	F-V slope	Pmax
SJ type	$p = 0.071$, $\eta^2 = 0.266$	$p = 0.630$, $\eta^2 = 0.022$	$p = 0.606$, $\eta^2 = 0.025$	$p = 0.013$, $\eta^2 = 0.445$
Procedure	$p = 0.845$, $\eta^2 = 0.004$	$p = 0.041$, $\eta^2 = 0.327$	$p = 0.084$, $\eta^2 = 0.247$	$p = 0.005$, $\eta^2 = 0.533$
Method	$p < 0.001$, $\eta^2 = 0.794$	$p = 0.002$, $\eta^2 = 0.607$	$p < 0.001$, $\eta^2 = 0.694$	$p = 0.025$, $\eta^2 = 0.378$
SJ type × Procedure	$p = 0.818$, $\eta^2 = 0.005$	$p = 0.022$, $\eta^2 = 0.391$	$p = 0.246$, $\eta^2 = 0.120$	$p = 0.016$, $\eta^2 = 0.426$
SJ type × Method	$p = 0.212$, $\eta^2 = 0.138$	$p = 0.631$, $\eta^2 = 0.022$	$p = 0.335$, $\eta^2 = 0.085$	$p = 0.548$, $\eta^2 = 0.034$
Procedure × Method	$p = 0.026$, $\eta^2 = 0.377$	$p = 0.155$, $\eta^2 = 0.175$	$p = 0.008$, $\eta^2 = 0.491$	$p = 0.592$, $\eta^2 = 0.027$
SJ type × Procedure × Method	$p = 0.837$, $\eta^2 = 0.004$	$p = 0.271$, $\eta^2 = 0.109$	$p = 0.386$, $\eta^2 = 0.069$	$p = 0.368$, $\eta^2 = 0.074$

F_0, maximum force; V_0, maximum velocity, F-V slope, slope of the force-velocity relationship; Pmax, maximum power; *p*, P-value; η^2, partial eta squared.





Maximum force (F_0)
SJ90 vs. SJ_{pref}
FP multiple p = 0.121, ES = 0.42 (-0.13, 0.97), r = 0.626
FP two-point p = 0.159, ES = 0.38 (-0.17, 0.94), r = 0.619
SAM multiple p = 0.089, ES = 0. 39 (-0.07, 0.85), r = 0.746
SAM two-point p = 0.114, ES = 0.36 (-0.10, 0.82), r = 0.747
FP vs. SAM
SJ90 multiple p = 0.818, ES = 0.04 (-0.33, 0.41), r = 0.835
SJ90 two-point p = 0.880, ES = -0.03 (-0.41, 0.35), r = 0.825
SJ_{pref} multiple p = 0.885, ES = -0.03 (-0.41, 0.36), r = 0.818
SJ_{pref} two-point p = 0.683, ES = -0.08 (-0.48, 0.33), r = 0.801
Three-point vs. Two-point
FP SJ90 p = 0.006, ES = 0.10 (0.03, 0.16), r = 0.995
FP SJ_{pref} p = 0.022, ES = 0.06 (0.01, 0.11), r = 0.997
SAM SJ90 p = 0.051, ES = 0.04 (0.00, 0.08), r = 0.998
SAM SJ_{pref} p = 0.468, ES = 0.01 (-0.02, 0.03), r = 0.999
-360 -240 -120 0 120 240 360
Raw mean difference (N)
Maximum velocity (V_0)
SJ90 vs. SJ_{pref}
FP multiple p = 0.291, ES = 0.34 (-0.34, 1.03), r = 0.423
FP two-point p = 0.245, ES = 0.38 (-0.30, 1.07), r = 0.419
SAM multiple p = 0.686, ES = -0.12 (-0.75, 0.51), r = 0.523
SAM two-point p = 0.665, ES = -0.13 (-0.74, 0.49), r = 0.538
FP vs. SAM
SJ90 multiple p = 0.009, ES = 0.79 (0.24, 1.34), r = 0.658
SJ90 two-point p = 0.005, ES = 0.84 (0.32, 1.37), r = 0.693
SJ_{pref} multiple p = 0.321, ES = 0.27 (-0.30, 0.83), r = 0.610
SJ_{pref} two-point p = 0.304, ES = 0.28 (-0.29, 0.84), r = 0.610
Three-point vs. Two-point
FP SJ90 p = 0.004, ES = -0.13 (-0.21, -0.05), r = 0.992
FP SJ_{pref} p = 0.030, ES = -0.09 (-0.17, -0.01), r = 0.992
SAM SJ90 p = 0.014, ES = -0.10 (-0.17, -0.02), r = 0.993
SAM SJ_{pref} p = 0.017, ES = -0.09 (-0.16, -0.02), r = 0.994
-0.45 -0.30 -0.15 0.00 0.15 0.30 0.45
Raw mean difference (m·s^{-1})
Force-velocity slope
SJ90 vs. SJ_{pref}
FP multiple p = 0.965, ES = 0.01 (-0.61, 0.64), r = 0.521
FP two-point p = 0.887, ES = -0.04 (-0.67, 0.58), r = 0.526
SAM multiple p = 0.255, ES = 0.36 (-0.30, 1.01), r = 0.472
SAM two-point p = 0.286, ES = 0.34 (-0.32, 1.00), r = 0.459
FP vs. SAM
SJ90 multiple p = 0.058, ES = -0.51 (-1.04, 0.02), r = 0.721
SJ90 two-point p = 0.034, ES = -0.59 (-1.12, -0.05), r = 0.718
SJ_{pref} multiple p = 0.385, ES = -0.24 (-0.81, 0.34), r = 0.604
SJ_{pref} two-point p = 0.299, ES = -0.28 (-0.86, 0.29), r = 0.608
Three-point vs. Two-point
FP SJ90 p = 0.003, ES = 0.14 (0.06, 0.22), r = 0.993
FP SJ_{pref} p = 0.014, ES = 0.10 (0.02, 0.18), r = 0.993
SAM SJ90 p = 0.015, ES = 0.09 (0.02, 0.15), r = 0.995
SAM SJ_{pref} p = 0.011, ES = 0.06 (0.02, 0.11), r = 0.997
-300 -200 -100 0 100 200 300
Raw mean difference (N·s·m^{-1})
Maximum power (P_{max})
SJ90 vs. SJ_{pref}
FP multiple p = 0.009, ES = 0.65 (0.20, 1.11), r = 0.771
FP two-point p = 0.013, ES = 0.65 (0.17, 1.13), r = 0.731
SAM multiple p = 0.045, ES = 0.24 (0.01, 0.48), r = 0.948
SAM two-point p = 0.,075 ES = 0.20 (-0.02, 0.43), r = 0.950
FP vs. SAM
SJ90 multiple p = 0.001, ES = 0.74 (0.39, 1.10), r = 0.846
SJ90 two-point p = 0.001, ES = 0.72 (0.39, 1.04), r = 0.871
SJ_{pref} multiple p = 0.207, ES = 0.19 (-0.12, 0.49), r = 0.893
SJ_{pref} two-point p = 0.263, ES = 0.16 (-0.14, 0.46), r = 0.890
Three-point vs. Two-point
FP SJ90 p = 0.199, ES = -0.04 (-0.09, 0.02), r = 0.996
FP SJ_{pref} p = 0.254, ES = -0.03 (-0.09, 0.02), r = 0.996
SAM SJ90 p = 0.151, ES = -0.04 (-0.09, 0.02), r = 0.998
SAM SJ_{pref} p = 0.027, ES = -0.06 (-0.12, -0.01), r = 0.997
-330 -220 -110 0 110 220 330
Raw mean difference (W)