Agreement in Squat Jump Force-Time Characteristics Between Smith Machine and Free-Weight Squat Jump Force-Time Characteristics

Yosuke Kotani,[1] Jason Lake,[1,2] Stuart N. Guppy,[1] Wayne Poon,[1] Kazunori Nosaka,[1] and G. Gregory Haff[1,3]

[1] School of Medical and Health Sciences, Edith Cowan University, Joondalup, Australia; [2] Department of Sport and Exercise Sciences, University of Chichester, Chichester, United Kingdom; and [3] Directorate of Psychology and Sport, University of Salford, Salford, Greater Manchester, United Kingdom

Journal of Strength and Conditioning Research Published Ahead of Print, May 29, 2023

Abstract

The purpose of this study was to determine whether squat jump (SJ) force-velocity (FV) and load-velocity (LV) profiles created using free-weights agree with profiles created with a Smith machine. Fifteen resistance-trained male subjects (age 5 26.4 6 2.5 years; height 5 1.75 6 0.09 m; body mass 5 82.6 6 13.4 kg) participated in this study. All subjects completed 2 familiarization and 2 experimental sessions using both the Smith machine and free-weight SJs each separated by 48 hours. During the experimental trials, progressively loaded SJs were performed in a quasi-randomized block order with loads between 21 kg and 100% of the subject's body mass. Agreement between exercise mode was determined with a weighted least products regression analysis. No fixed or proportional bias was noted between exercise modes when using peak velocity (PV) and mean velocity (MV) to create an FV profile. There was no fixed and proportional bias present for the LV profile when the profile was created with PV. When the LV profile was calculated from MV, fixed and proportional bias were present, indicating that MVs were significantly different between exercise modes. In addition, the free-weight FV and LV profiles exhibited poor to good relative and good to poor absolute reliability. Furthermore, when created using the Smith machine, both profiles exhibited poor to moderate relative and absolute reliability. Based on these data, caution should be used when interpreting LV and FV profiles created with these 2 methods.

Key Words: force generation capacity, velocity-based training, training direction, training load prescription, exercise mode, jump performance

Introduction

Manipulating training variables is critical when creating resistance training programs that are designed to optimize performance adaptations such as increasing maximum strength, vertical jump, and sprint performance ([28]). One possible method for manipulating training variables is to monitor movement velocity. Fundamentally, the quantification of movement velocity during resistance training can be used to establish either a load-velocity (LV) or a force-velocity (FV) profile. The LV profile establishes the relationship between external loads and velocity of movement and can be used as a programming tool ([36]). As a result of this relationship, some authors have suggested that the LV profile may be useful for predicting the 1 repetition maximum (1RM) ([4,11]), whereas others have questioned the efficacy of this practice ([1,14]). In addition, it has been proposed that training programs can be designed based on velocities of movement instead of more traditional practices of prescribing training load ([35]).

When the LV profile is used to program training loads, the athlete is given a targeted movement velocity and the load on the barbell is manipulated on a set-by-set basis to ensure that the velocity of movement is maintained ([35]). Alternatively, the FV profile is used as a diagnostic tool, which allows the coach to determine whether the athlete is force or velocity dominant ([12,13]). Based on this information, the coach can then make programmatic decisions that influence the ability of the athlete's training program to address the determined deficit ([12,13,31]). Although there is theoretical and some scientific support for implementing these programming and diagnostic strategies ([12,13,35]), it is important to note that the accuracy of prescribing loads and training directions based on these profiles is largely dependent on the accuracy and reliability of the input variables used when calculating these profile ([3,8]).

Several factors can impact the ability to reliably create either the FV or LV profile, including the type of measurement device, biological factors, loading paradigm used during testing, athlete's maximal strength levels, exercise used during testing, and exercise mode ([24]). When considering the exercise mode (i.e., free-weight vs. machine), it is possible that the increased horizontal displacement associated with exercises performed with free-weights may negatively impact the reliability of the velocity measurements made when constructing each profile ([10,27,30]). Conversely, the reduced horizontal movement associated with using the Smith machine is likely to increase the reliability of the LV or FV profile ([7,10,26]). Although the logic surrounding the difference in horizontal movement between free-weight and Smith machine squat jumps (SJs) is sound, García-Ramos et al. ([6]) have reported that exercise performed with free-weights may result in more reliable data. In particular, performing the free-weight SJ with progressively increasing loads to determine the slope of the FV profile was shown to be slightly more reliable (ICC = 0.81–0.82, CV% = 7.2–12.6) when compared with FV profiles created from SJs performed with a Smith machine (ICC = 0.77–0.82, CV% = 13.0–14.0) ([6]). Conversely, Valenzuela et al. ([34]) have reported that the theoretical maximal velocity determined with SJs performed with free-weights is less reliable (ICC = 0.07, CV% = 34.5) than those achieved when SJs are performed with a Smith machine (ICC = 0.77, CV% = 12.6). Because the slope of the FV profile is impacted by the theoretical maximal velocity, it is likely that the reliability of the FV profile may be influenced similarly. Because of the conflicting data within the contemporary scientific literature, further study comparing SJs performed with free-weights and the Smith machine is warranted.

As the FV profile generated from SJs performed with free-weights or with a Smith machine results in different FV imbalances ([34]) and slopes ([6]), using these 2 tests interchangeably may result in a misdiagnosis of the athlete's individual FV imbalance. This may lead the coach make an incorrect training decision, resulting in the wrong deficit being targeted. Therefore, the primary purpose of this study was to determine whether the FV and LV profiles obtained during SJs performed using free-weights agree with profiles determined with the use of a Smith machine. Based on the available literature ([7,10,26]), we hypothesized that there would be agreement between the FV and LV profiles determined with SJs performed with free-weights and a Smith machine.

Methods

Experimental Approach to the Problem

All subjects performed 4 sessions separated by 48 hours. During session 1, a signed informed consent form was obtained, and baseline measures including height and body mass (BM) were collected. The subjects were then randomly assigned to a maximum back squat (1RM) testing order where they were either first tested with free-weights or the Smith machine. After the strength test (free-weight or Smith machine), the subjects were comprehensively familiarized with the corresponding SJ protocol (i.e., free-weight or Smith machine) to ensure all subjects were able to consistently perform loaded SJs in the mode of exercise tested during the session. During session 2, the subject's 1RM squat was determined with the mode not tested in session 1 (free-weight or Smith machine). As with session 1, a comprehensive SJ familiarization session was performed after the strength test with the mode (free-weight or Smith machine) of exercise tested during the session. In session 3, subjects performed SJs using the mode used in session 1 with 6 loads ranging from 21 kg to 100% of their BM in a quasi-randomized block order. For session 4, subjects repeated the same loading pattern with the experimental protocol using the mode tested in session 2.

Subjects

Fifteen resistance-trained male subjects (mean ± *SD*, age = 26.4 ± 2.5 years; height = 1.75 ± 0.09 m; BM = 82.6 ± 13.4 kg; free-weight back squat 1RM = 1.9 ± 0.2 $kg \cdot kg^{-1}$; Smith machine back squat 1RM = 2.0 ± 0.2 $kg \cdot kg^{-1}$) were recruited to undertake this study. All subjects read and signed an informed consent form before participating in this research ethics committee approved study in accordance with Edith Cowan University Human Research Ethics Committee guidelines (Project 20335). To be included in this study, subjects were required to be free of any injuries that would prevent them from performing any of the lifting tasks pain-free and with maximum effort and be able to back squat a minimum of 1.5x BM in both the free-weight and Smith machine back squat. All subjects were also screened for strength training background with the use of a standardized questionnaire.

Procedures

One Repetition Maximum Testing

The back squat depth, the knee, and hip angles in either the free-weight or Smith machine were measured using a hand-held goniometer (Exacta Goniometer, CA). During this session, the subjects self-selected foot width was recorded based on the methods of Tufano et al. ([33]) to allow for foot placement replication during all testing sessions. Briefly, the subjects heal, and toe locations were photographed with an iPhone (Apple Inc, Cupertino, CA), whereas the subjects were standing on the force plate, which was marked with a horizontal-vertical grid that intersected at 1-cm intervals. A standardized dynamic warm-up was then performed followed by the 1RM back squat protocol with either a standard Olympic barbell (Eleiko, Halmstad, Sweden) or in a Smith machine (Fitness Technology Inc., Australia; 21-kg bar) according to previously established methods ([2]). Briefly, subjects were instructed to squat to the predetermined squat depth, which was defined by an elastic cord placed at a position corresponding to a 90° knee angle ([32]), and then stand up as soon as their gluteus maximus touched the cord. Subjects performed 3 repetitions at 40 and 60% of their estimated 1RM, then performed 1 repetition at 80, 90, and 100% of the estimated 1RM. At this point, they attempted their 1RM with the load being adjusted by 0.5- and 2.5-kg increments until they could no longer successfully perform the lift. All subjects achieved their maximum within five 1RM attempts. Subjects were allowed to use a weightlifting belt, as needed, during both the free-weight and Smith machine back squat 1RM tests. If a belt was used in the back squat 1RM test, the subjects were required to use the belt in all remaining testing sessions. After the completion of the 1RM test, subjects performed a comprehensive SJ familiarization session with the same mode used to test the 1RM. During each familiarization, subjects were randomly exposed to loads from each of the 3 loading blocks used within this study: (a) ∼30% (21 kg), 40%, (b) 60%, 80%, and (c) 100% of BM. This was performed to ensure that the subjects were familiar with the spectrum of loads used in this study.

Squat Jump Testing

The SJ starting position and self-selected SJ foot width for either the free-weight or Smith machine were recorded and standardized for each session using the methods outlined for the back squat 1RM. Before initiating the SJ test, all subjects performed a self-selected dynamic warm-up (i.e., BM squat, lunge, leg and arm swing, skip, and submaximal SJ) that was recorded and kept consistent in the remaining session ([16]). After completing their individualized warm-up, all subjects performed a series of SJs that were divided into 3 progressively increasing blocks: (a) 21 kg, 40%, (b) 60%, 80%, and (c) 100% of BM. The loads in each block were randomized, and the blocks were performed in an ascending order (i.e., from block 1 to block 3). Subjects performed 2 SJs with 1 minute between jumps and were given 2 minutes of recovery between loads ([16]). During all SJs, subjects were required to place the barbell across their shoulders and maintain contact with the barbell during each jump. When performing the Smith machine SJs, the initial load was 21 kg (25.5 ± 4.5% of BM), and the load was adjusted for each % of BM required. During the free-weight SJ, 0.5 kgs were added to each side of the barbell to make the weight on the barbell equal to 21 kg to align with the barbell weight in the Smith machine. During both modes of testing, subjects were instructed to squat down to an elastic cord set at their previously determined 90° knee angle ([16]). This position was held for 2 seconds, to remove the influence of the stretch-shortening cycle, and then the subjects jumped maximally when instructed to "*Jump!*". Repetitions were repeated if the investigator observed the barbell leaving the subject's shoulders or if a visually obvious countermovement before initiation of the propulsive phase was present during real-time force trace observation ([23]). To limit fatigue, no more than 3 trials (mean = 2.24 ± 0.15 trials) were performed at any given load. All trials were performed while standing on dual portable force plates (PS-2141; PASCO Scientific, CA), with vertical ground reaction forces collected at 1000 Hz using PASCO Capstone software (version 2.2.1 PASCO Scientific).

Data Analysis

All data were analyzed as an unfiltered summated force-time curve in a custom Excel spreadsheet (Microsoft, Redmond, WA). The start of the jump was identified as the point at which force exceeded system weight (SW) + 5 SDs, where SW was calculated as the average force during a 1-second "quiet standing" period. Take-off was then identified using the three-step process outlined by Lake et al. ([18]). The portion of the force-time curve between the start of the jump and take-off was defined as the concentric phase. The velocity of the system center of mass was calculated by dividing the net force by system mass and integrating the acceleration-time record using the trapezoid rule ([19]). PV was defined as the highest instantaneous velocity, and MV was defined as average velocity during the concentric phase, respectively ([18]). The trial with the highest PV in each exercise mode was carried forward for the agreement analysis, whereas both trials were used for the analysis of within-session reliability ([17]).

A custom Excel spreadsheet (Microsoft, Redmond, WA) was used to perform individualized linear regression analyses of the velocity and force, as well as velocity and load, values obtained from each of the SJs performed across the load spectrum. These analyses were used to determine the theoretical maximum force (F_0), theoretical maximum load (L_0), theoretical maximum velocity (V_0), and slope of these profiles ([12,16,25,29]). The trial with the highest PV at each load tested was used for the agreement analysis, whereas both trials collected at each load were used for the within-session reliability analyses.

Statistical Analyses

Normality of distribution was assessed using the Shapiro-Wilk test and visual inspection of Q-Q plots. Agreement between free-weight and Smith machine SJ-PF, -PV, -MF, and -MV at each load, as well as F_0, V_0, L_0, and slope of both profiles, was assessed using weighted least products regression ([21]). Fixed bias was present if the 95% confidence intervals (CIs) for the intercept did not include zero, whereas proportional bias was present if the 95% CIs for the slope did not include 1 ([21]). Weighted least products regression analyses were performed in SPSS 26.0 (IBM Corp, NY) ([22]). Test-retest reliability was determined by calculating the intraclass correlation coefficient (ICC; type 3,1), coefficient of variation (CV), and 95% CIs in an Excel spreadsheet ([9]). ICC 95% CI lower bound values were interpreted as poor (<0.5), moderate (0.5–0.75), good (>0.75–0.9), and excellent (>0.9) ([15]). The magnitude of the CV was interpreted as poor (>10%), moderate (5–10%), and good (<5%) ([5]).

Results

There was no fixed or proportional bias present for the FV profile variables calculated with PV and PF as well as MV and MF when SJs were performed with the different exercise modes (Table 1). In addition, no fixed or proportional bias was present for the LV profile variables between exercise modes when determined with PV. Fixed and proportional bias was present for V_0, and slope of the LV profile as well as proportional bias was present for L_0 when these were calculated with MV, which shows that there were significant fixed and proportional differences between the predicted and actual values.

No fixed or proportional bias was present for PV and MV between exercise modes across all loads (Table 2). In addition, there was no fixed or proportional bias present between the free-weight and Smith machine for PF across all loads (Table 3). However, when MF was compared between the free-weight and Smith machine, there was fixed and proportional bias present at 100% of BM.

Table 1 - Comparison of the FV and LV profile variables determined from the free-weight and Smith machine squat jumps.*†

	Peak velocity		Mean velocity	
	Slope (95% CI)	**Intercept (95% CI)**	**Slope (95% CI)**	**Intercept (95% CI)**
FV				
V_0	1.129 (0.790, 1.469)	−0.577 (−2.103, 0.948)	0.989 (0.281, 1.686)	−0.176 (−1.488, 1.137)
F_0	0.959 (0.278, 1.641)	1.000 (−2,342.653, 2,344.653)	0.879 (−0.027, 1.785)	1.000 (−2,795.153, 2,797.153)
Slope	1.102 (0.347, 1.858)	157.171 (−415.825, 730.167)	0.782 (0.063, 1.501)	70.317 (−1055.060, 1195.695)
LV				
V_0	0.923 (0.456, 1.390)	0.162 (−0.925, 1.250)	0.005 (−0.243, 0.292)§	0.952 (0.441, 1.463)‡
L_0	1.015 (0.633, 1.398)	-13.369 (−98.905, 72.167)	0.053 (−0.004, 0.111)§	-5.496 (−211.483, 200.49)
Slope	0.909 (0.540, 1.278)	-7.392 (−41.854, 27.069)	−0.090 (−0.157, −0.023)§	-320.328 (−422.467, −218.189)‡

*CI = confidence interval; FV = force-velocity; LV = load-velocity.
†If the 95% CI for the intercept does not include 0, there is fixed bias present; if the 95% CI for slope does not include 1.0, there is proportional bias present.
‡Fixed bias was present.
§Proportional bias was present.

Table 2 - Comparison of the peak and mean velocity during the free-weight and Smith machine squat jumps.*†

	Peak velocity		Mean velocity	
Load	**Slope (95% CI)**	**Intercept (95% CI)**	**Slope (95% CI)**	**Intercept (95% CI)**
21 kg	1.035 (0.499, 1.570)	−0.097 (−1.227, 1.033)	1.248 (0.694, 1.801)	−0.224 (−0.746, 0.297)
40% BM	0.914 (0.536, 1.291)	0.153 (−0.604, 0.910)	1.333 (0.320, 2.346)	−0.324 (−-1.284, 0.636)
60% BM	0.788 (0.298, 1.278)	0.333 (−0.533, 1.218)	1.368 (0.869, 1.868)	−0.354 (−0.762, 0.054)
80% BM	1.059 (0.725, 1.392)	−0.133 (−0.718, 0.453)	0.879 (0.363, 1.396)	0.132 (−0.272, 0.537)
100% BM	1.059 (0.615, 1.502)	−0.152 (−0.902, 0.598)	1.026 (0.196, 1.856)	−0.020 (−0.599, 0.599)

*CI = confidence interval; BM = body mass.
†If the 95% CI for the intercept does not include 0, there is fixed bias present; if the 95% CI for slope does not include 1.0, there is proportional bias present.

Table 3 - Comparison of the peak and mean force during the free-weight and Smith machine squat jumps.*†

	Peak force		Mean force	
Load	Slope (95% CI)	Intercept (95% CI)	Slope (95% CI)	Intercept (95% CI)
21 kg	0.955 (0.932, 1.059)	1.000 (−99.962, 101.962)	0.991 (0.759, 1.223)	1.000 (−357.133, 359.133)
40% BM	0.997 (0.918, 1.076)	1.000 (−170.195, 172.195)	0.987 (0.818, 1.157)	1.000 (−289.360, 291.360)
60% BM	0.982 (0.951, 1.013)	1.000 (1.000, 1.000)	0.975 (0.756, 1.270)	1.000 (−409.301, 411.301)
80% BM	0.971 (0.926, 1.017)	1.000 (−98.334, 100.334)	0.986 (0.702, 1.270)	1.000 (−562.354, 564.354)
100% BM	1.003 (0.814, 1.192)	1.000 (−488.177, 490.117)	1.123 (1.095, 1.151)§	-243.795 (−282.097. -205.494)‡

*CI = confidence interval; BM = body mass.

†If the 95% CI for the intercept does not include 0, there is fixed bias present; if the 95% CI for slope does not include 1.0, there is proportional bias present.

‡Fixed bias was present.

§Proportional bias was present.

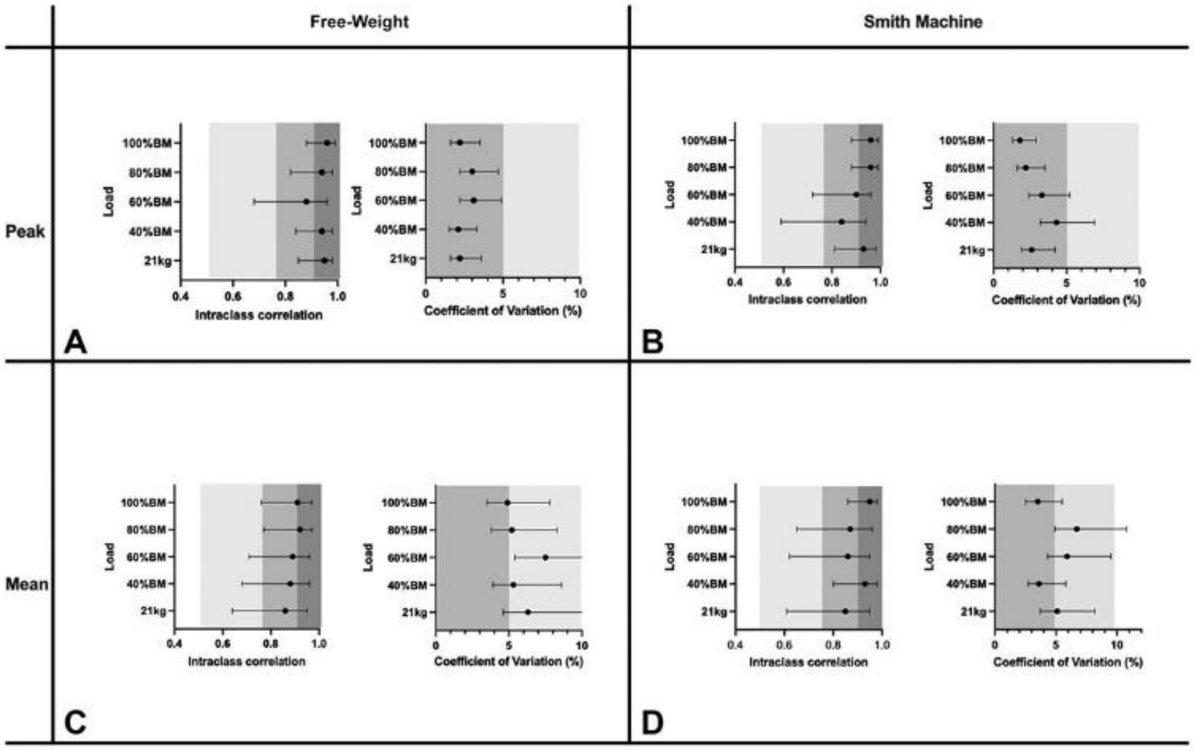
When the SJ was performed using free-weights, moderate to good relative reliability and good absolute reliability were displayed for PV at each load (Figure 1A). When the SJ was performed in the Smith machine, moderate to good relative reliability and moderate to good absolute reliability were exhibited for PV (Figure 1B).

When MV was measured during the free-weight SJ, moderate to good relative reliability and poor to moderate absolute reliability were exhibited at each load (Figure 1C). There was moderate to good relative reliability and poor to moderate absolute reliability when MV determined during Smith machine SJs (Figure 1D).

In addition, when the FV profile was calculated using PF and PV values obtained from SJs performed with a Smith machine, there was poor relative and absolute reliability for the F_0, moderate relative reliability and poor absolute reliability for the V_0, and poor relative and absolute reliability for the slope (Figure 2B). When the FV profile was created using PF and PV values obtained from the free-weight SJ, there was moderate relative reliability and poor absolute reliability for F_0, V_0, and poor relative and absolute reliability for the slope (Figure 2A).

Furthermore, when the MF and MV obtained from SJs performed with a Smith machine were used to calculate the FV profile, there was a poor relative and absolute reliability for F_0, poor relative and absolute reliability for the V_0, and poor relative and absolute reliability for the slope (Figure 2D). When MF and MV from SJs performed with free-weights were used to create an FV profile, there was a poor relative and absolute reliability for F_0, moderate relative reliability and poor absolute reliability for the V_0, and poor relative and absolute reliability for the slope (Figure 2C).

Figure 1. Comparison of the reliability of peak (PV) and mean velocity (MV) during a squat jump between the free-weight and Smith machine. A) ICC and CV% for the PV free-weight SJ, (B) ICC and CV% for the PV Smith machine SJ, (C) ICC and CV% for the MV free-weight SJ, and (D) ICC and CV% for the MV Smith machine SJ. The shaded areas represent the levels of relative and absolute reliability (ICC <0.5 = poor, not shaded; ICC 0.5–0.75 = moderate, shaded in light gray; ICC >0.75–0.9 = good, shaded in medium gray; ICC >0.9 = excellent, shaded in dark gray; CV <5% = good, shaded in medium gray; CV 5–10% = moderate, shaded in medium gray; and CV >10% = poor, shaded in white); error bars represent 95% confidence intervals, ICC = intraclass correlation, CV% = coefficient variation, %BM = percent body mass.



When the LV profile was determined based on SJ PV determined using the Smith machine, there was poor relative and absolute reliability for L_0, good relative reliability and moderate absolute reliability for V_0, and poor relative and absolute reliability for the slope (Figure 3B). When free-weights were used to create the LV profile using PV, there was a moderate relative reliability and poor absolute reliability for L_0, good relative and absolute reliability for V_0, and moderate relative reliability and poor absolute reliability for the slope (Figure 3A).

When the LV profile variables determined based on SJs performed in a Smith machine were calculated using MV, poor relative and absolute reliability was exhibited for L_0, moderate relative and absolute reliability for the V_0, and poor relative and absolute reliability for the slope (Figure 3D). When the free-weights were used to calculate the LV profile using MV, there was moderate relative reliability and poor absolute reliability for L_0, good relative reliability and moderate absolute reliability for the V_0, and poor relative and absolute reliability for the slope (Figure 3C).

Figure 2. Comparison of the reliability of the FV profile variables during a squat jump between the free-weight and Smith machine when calculated from peak velocity (PV) and force (PF) as well as mean velocity (MV) and force (MF). A) ICC and CV% for the free-weight SJ with PV and PF, (B) ICC and CV% for the Smith machine SJ with PV and PF, (C) ICC and CV% for the free-weight SJ with MV and MF, and (D) ICC and CV% for the Smith machine SJ with MV and MF. The shaded areas represent the levels of relative and absolute reliability (ICC <0.5 = poor, not shaded; ICC 0.5–0.75 = moderate, shaded in light gray; ICC >0.75–0.9 = good, shaded in medium gray; ICC >0.9 = excellent, shaded in dark gray; CV <5% = good, shaded in medium gray; CV 5–10% = moderate, shaded in medium gray; and CV >10% = poor, shaded in white); error bars represent 95% confidence intervals, ICC = intraclass correlation, CV% = coefficient variation, %BM = percent body mass.

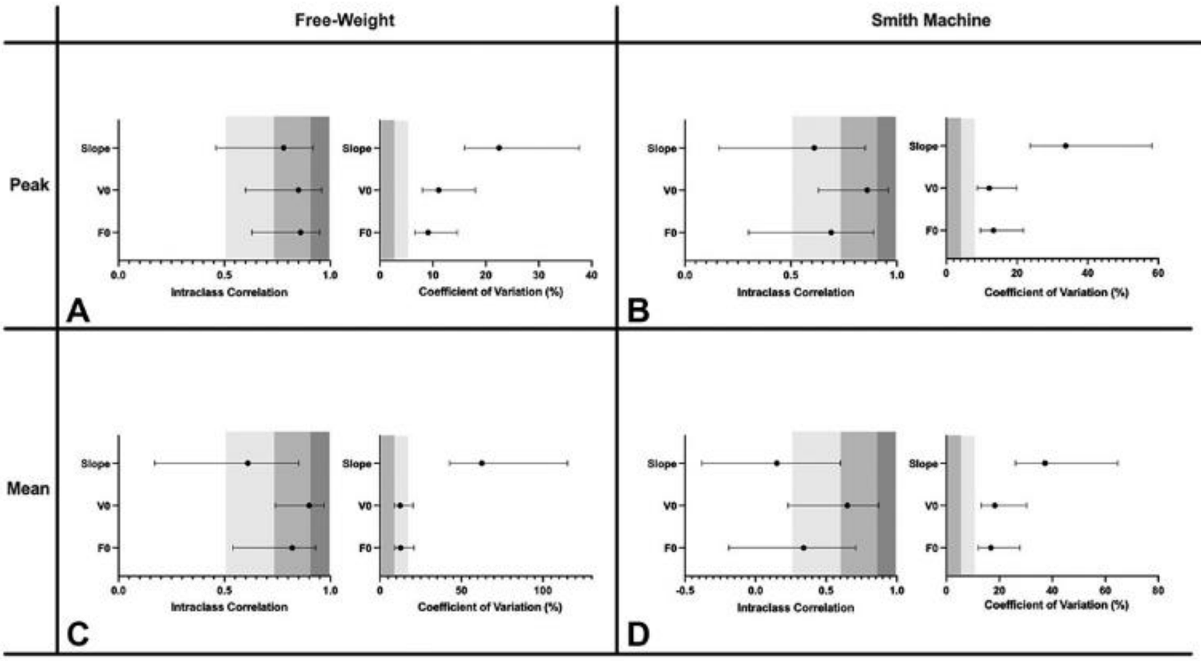
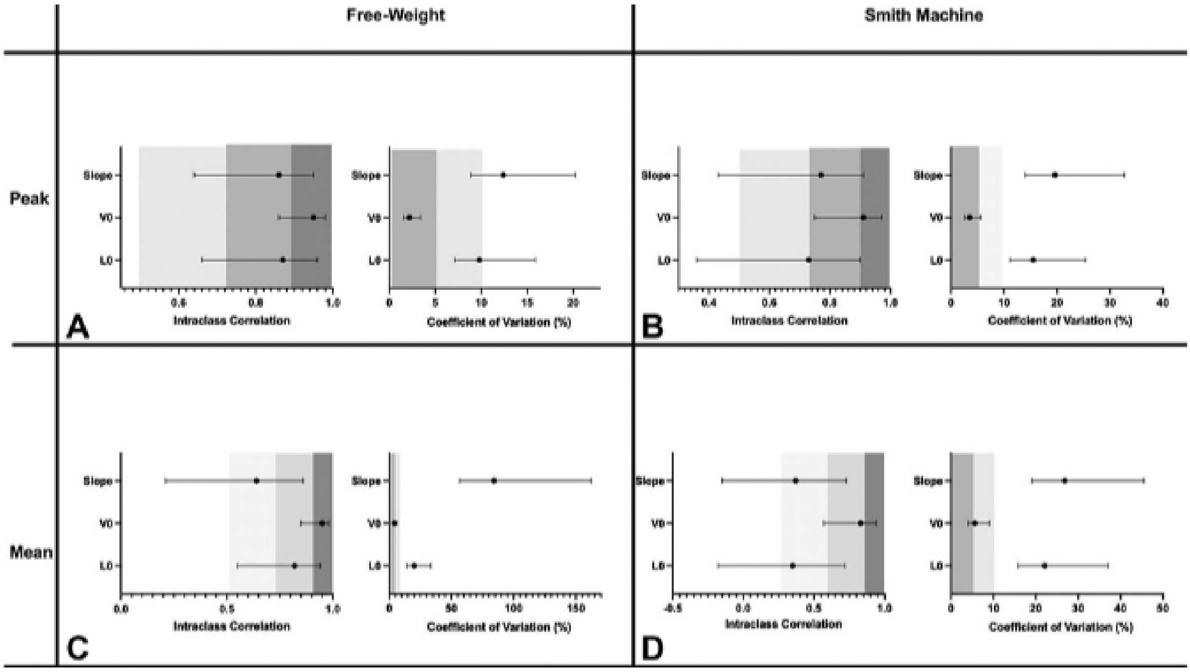


Figure 3. Comparison of the reliability of the VL profile variables during a squat jump between the free-weight and Smith machine when calculated from peak (PV) and mean velocity (MV). A) ICC and CV% for the PV free-weight SJ, (B) ICC and CV% for the PV Smith machine SJ, (C) ICC and CV% for the MV free-weight SJ, and (D) ICC and CV% for the MV Smith machine SJ. The shaded areas represent the levels of relative and absolute reliability (ICC <0.5 = poor, not shaded; ICC 0.5–0.75 = moderate, shaded in light gray; ICC >0.75–0.9 = good, shaded in medium gray; ICC >0.9 = excellent, shaded in dark gray; CV <5% = good, shaded in medium gray; CV 5–10% = moderate, shaded in medium gray; and CV >10% = poor, shaded in white); error bars represent 95% confidence intervals, ICC = intraclass correlation, CV% = coefficient variation, %BM = percent body mass.



Free-Weight
Smith Machine
Peak
Mean
Slope
V0
L0
Intraclass Correlation
Coefficient of Variation (%)
A
B
C
D

Discussion

The primary purpose of this study was to determine the level of agreement between the FV and LV profiles created from SJs performed with either free-weights or a Smith machine. The primary finding of this study was that the FV profiles created with free-weights and the Smith machine agreed regardless of whether PF or MF and PV or MV were used to create these profiles. Furthermore, there was agreement between the LV profiles determined with the use of free-weights and the Smith machine when PV was used to create the profile. However, when MV was used to create the LV profile, there was a lack of agreement between the profiles. The secondary purpose of this study was to determine whether there are differences in the reliability of the FV and LV profiles created with each exercise mode. When free-weights were used to create these profiles, there was poor to good relative and absolute reliability, regardless of whether PV or MV was used. When the Smith machine was used to create these profiles, there was poor to moderate relative and absolute reliability, regardless of whether PV or MV was used.

To the best of authors' knowledge, there is limited research that directly investigates the agreement between FV profiles created from SJs performed with free-weights and within a Smith machine ([6,34]). Although previous studies have attempted to compare the impact of exercise mode on the ability to create an FV profile ([6,34]), the statistical methods used in these studies make it difficult to compare with the results of this study ([6,34]). For example, Valenzuela et al. ([34]) reported that when FV profiles are calculated based on the MV and MF, there were differences in V_0 (ICC = 0.20, p = 0.104), F_0 (ICC = 0.45, p = 0.008), and FV imbalance (ICC = 0.22, p = 0.025) between the profiles performed with free-weights and with a Smith machine. Although there is no consensus on which statistical test is most appropriate for the assessment of agreement between measures, there are limitations associated with using correlational analyses ([20,21,37]). The principal limitation of these methods is that they are unable to determine both fixed (i.e., a constant difference between criterion [Smith machine] and the value predicted by the alternative method [free-weights]) and proportional bias (a difference between the criterion [Smith machine] and the alternative method [free-weights] that increases in proportion to the magnitude of the measure) ([20,21]). Because of these limitations, it has been recommended that method comparisons use a least products regression analysis because this method allows the investigator to establish whether the predicted values are the same, both from a fixed and proportional bias perspective ([20–22]).

In another study that examined the differences between the FV profiles created with SJs performed with free-weights or within a Smith machine, it was reported that there were differences between the slope of the FV profiles created with MF and MV determined with each mode of exercise ([6]). Based on these findings, it might be suggested that the FV profiles determined from SJs performed with these 2 modes of exercise cannot be used interchangeably. In contrast to the findings of García-Ramos et al. ([6]), we determined that the FV profile created from SJs performed with free-weights can be used interchangeably with the FV profile that was created with the Smith machine. This conclusion was based on the fact that regardless of if PV and PF or MV and MF was used to create the FV profile, there was no fixed or proportional bias present. As García-Ramos et al. ([6]) used a statistical approach that was unable to determine bias, it is difficult to determine whether their data also exhibit the same lack of bias between exercise modes as this study.

Although there are no known studies that have directly compared the impact of using different exercise modes to develop an SJ LV profile, there are studies that have examined the creation of these profiles with free-weights ([13]) or with a Smith machine ([7]) in isolation. For example, Kotani et al. ([16]) reported that when a free-weight SJ LV profile was created from PV obtained from a force plate, the profile was not reliable between days. Conversely, García-Ramos et al. ([7]) reported that when the LV profile was created with SJs performed within a Smith machine, there is a higher reliability based on a lower CV% (PV = 2.0–2.8) and a higher ICC (PV = 0.97–0.99). Because of these divergent findings, it is possible that there may also be differences in the slope of the LV profile and reliability of the velocity measurements, which may impact the level of agreement between profiles created with each mode. In this study, there was agreement between the LV profile created from PV determined with SJs performed with either free-weights or the Smith machine. Based on the lack of fixed or proportional bias between these exercise modes, it seems that these 2 profiles can be used interchangeably. Conversely, when MV is used to construct these profiles, there is a lack of agreement between these modes of exercise. Specifically, SJ LV profiles created with free-weights or a Smith machine should not be used interchangeably because of the presence of fixed and proportional bias between the predicted and actual values. Because of the lack of existing research examining the agreement between free-weight and Smith machine SJs, further investigation is warranted to verify the findings of this study.

Although some research has been presented in the scientific literature that has examined the reliability of the SJ FV profile, to the best of our knowledge, there is limited research looking at the reliability of the SJ LV profile ([16]). In this study, when PV was used to create the LV profile, there was poor to good relative and absolute reliability regardless of the mode of exercise. When MV was used to create the LV profile, there was poor to moderate relative and absolute reliability regardless of exercise mode. These results are similar to those reported by Kotani et al. ([16]), who evaluated the reliability of the LV profile created by measuring PVs and MVs with a series of progressively increasing loads determined during free-weight SJs performed on a force platform. Specifically, Kotani et al. ([16]) reported poor to moderate reliability when PV (ICC = 0.83, CV% = 10.7) and MV (ICC = 0.77, CV% = 15.1) are used to create the SJ LV profile. Based on the reliabilities presented in this study and the study by Kotani et al. ([16]), strength and conditioning professionals must consider the impact of reliability on the utility of the LV profile and potentially avoid using these profiles to guide training decisions or prescribe loads for the SJ.

Although we have reported that FV and LV profiles created with SJs agree when performed with free-weights or with a Smith machine, there are several potential limitations to our study. Although we attempted to ensure our subjects were comprehensively familiarized with the SJ protocols used, it is possible based on the work of Meylan et al. ([24]) that more familiarization sessions may have been warranted in order maximize the reliability of the FV and LV profile measurements. Although increasing the number of familiarization session would directly impact the reliability of the various measurements, it is unlikely that this impacted the levels of agreement between the modes used to create the FV and LV profiles. In addition, based on the fact that we used percentages of BM to provide the loads that were used to create the FV and LV profiles, we cannot discount the impact of maximal strength on the reliability of the measures. As such, future research should examine the impact of maximal strength on the FV and LV profiles by comparing profiles created based on absolute loads, percentages of BM, and percentages of 1RM back squat.

Practical Applications

Based on the results of this study, there was agreement between the FV profiles created for SJs performed with free-weights and a Smith machine regardless of whether PV and PF or MV and MF were used. In addition, the LV profile for progressively loaded SJs only displayed agreement between exercise modes when the profile was calculated with PV. Based on these findings, it can be recommended that FV profiles can be created from SJs performed with progressively increasing loads on either free-weights or a Smith machine. When LV profiles are created from progressively loaded SJs, only profiles created from PV can be used interchangeably.

Acknowledgements

The authors thank the subjects for their time and efforts during the study and Maria Grammenou and Tsuyoshi Nagatani for their assistance with data collection. This study was supported by an Australian Government Research Training Program scholarship. J. Lake provides consultancy services and is Director of Education for Hawkin Dynamics, a portable force-plate manufacturer and analysis software company. Hawkin Dynamics' products were not used in this study, and the company did not play any role in the design of the study, collection and analysis of the data, or the preparation of and decision to publish this manuscript. The other authors have no conflicts of interest to declare.

References

1. Banyard HG, Nosaka K, Haff GG. Reliability and validity of the load–velocity relationship to predict the 1RM back squat. J Strength Cond Res 31: 1897–1904, 2017.

2. Banyard HG, Nosaka K, Sato K, Haff GG. Validity of various methods for determining velocity, force, and power in the back squat. Int J Sports Physiol Perform 12: 1170–1176, 2017.

3. Banyard HG, Nosaka K, Vernon AD, Haff GG. The reliability of individualized load–velocity profiles. Int J Sports Physiol Perform 13: 763–769, 2018.

4. Bazuelo-Ruiz B, Padial P, García-Ramos A, et al. Predicting maximal dynamic strength from the load-velocity relationship in squat exercise. J Strength Cond Res 29: 1999–2005, 2015.

5. Duthie G, Pyne D, Hooper S. The reliability of video based time motion analysis. J Hum Mov Stud 44: 259–272, 2003.

6. García-Ramos A, Feriche B, Pérez-Castilla A, Padial P, Jaric S. Assessment of leg muscles mechanical capacities: Which jump, loading, and variable type provide the most reliable outcomes? Eur J Sport Sci 17: 690–698, 2017.

7. García-Ramos A, Stirn I, Strojnik V, et al. Comparison of the force-velocity-and power-time curves recorded with a force plate and a linear velocity transducer. Sports BioMech 15: 329–341, 2016.

8. Giroux C, Rabita G, Chollet D, Guilhem G. What is the best method for assessing lower limb force-velocity relationship? Int J Sports Med 36: 143–149, 2014.

9. Hopkins WG. Spreadsheets for analysis of validity and reliability. Sportscience 19: 36–44, 2015.

10. Hughes LJ, Peiffer JJ, Scott BR. Load-velocity relationship 1RM predictions: A comparison of smith machine and free-weight exercise. J Sports Sci 38: 2562–2568, 2020.

11. Janicijevic D, Jukic I, Weakley J, García-Ramos A. Bench press 1-repetition maximum estimation through the individualized load–velocity relationship: Comparison of different regression models and minimal velocity thresholds. Int J Sports Physiol Perform 16: 1074–1081, 2021.–.

12. Jimenez-Reyes P, Samozino P, Brughelli M, Morin JB. Effectiveness of an individualized training based on force-velocity profiling during jumping. Front Physiol 7: 1–13, 2017.

13. Jiménez-Reyes P, Samozino P, Morin JB. Optimized training for jumping performance using the force-velocity imbalance: Individual adaptation kinetics. PLoS One 14: e0216681, 2019.

14. Jukic I, García-Ramos A, Malecek J, Omcirk D, Tufano JJ. Validity of load-velocity relationship to predict 1 repetition maximum during deadlifts performed with and without lifting straps: The accuracy of six prediction models. J Strength Cond Res 36: 902–910, 2020.

15. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med 15: 155–163, 2016.

16. Kotani Y, Lake J, Guppy SN, et al. Reliability of the squat jump force-velocity and load-velocity profiles. J Strength Cond Res 36: 3000–3007, 2022.

17. Lake J, Augustus S, Austin K, et al. The reliability and validity of the bar-mounted Push Band(TM) 2.0 during bench press with moderate and heavy loads. J Sports Sci 37: 2685–2690, 2019.

18. Lake JP, Mundy PD, Comfort P, et al. Effect of barbell load on vertical jump landing force-time characteristics. J Strength Cond Res 35: 25–32, 2021.

19. Linthorne NP. Analysis of standing vertical jumps using a force platform. Am J Phys 69: 1198–1204, 2001.

20. Ludbrook J. Comparing methods of measurement. Clin Exp Pharmacol Physiol 24: 193–203, 1997.

21. Ludbrook J. Statistical techniques for comparing measurers and methods of measurement: A critical review. Clin Exp Pharmacol Physiol 29: 527–536, 2002.

22. Ludbrook J. A primer for biomedical scientists on how to execute model II linear regression analysis. Clin Exp Pharmacol Physiol 39: 329–335, 2012.

23. McMahon JJ, Lake JP, Suchomel TJ. Vertical jump testing. In: Assessment in Strength and Conditioning. Comfort P, ed. Oxon, UK: Routledge, 2019. pp. 96–118.

24. Meylan CM, Cronin JB, Oliver JL, et al. The reliability of isoinertial force-velocity-power profiling and maximal strength assessment in youth. Sports BioMech 14: 68–80, 2015.

25. Padulo J, Migliaccio GM, Ardigò LP, et al. Lower limb force, velocity, power capabilities during leg press and squat movements. Int J Sports Med 38: 1083–1089, 2017.

26. Pérez-Castilla A, Jiménez-Reyes P, Haff GG, García-Ramos A. Assessment of the loaded squat jump and countermovement jump exercises with a linear velocity transducer: Which velocity variable provides the highest reliability? Sports BioMech 20: 247–260, 2021.

27. Perez-Castilla A, McMahon JJ, Comfort P, Garcia-Ramos A. Assessment of loaded squat jump height with a free-weight barbell and smith machine: Comparison of the takeoff velocity and flight time procedures. J Strength Cond Res 34: 671–677, 2020.

28. Riscart-López J, Rendeiro-Pinho G, Mil-Homens P, et al. Effects of four different velocity-based training programming models on strength gains and physical performance. J Strength Condit Res 35: 596–603, 2021.

29. Samozino P, Edouard P, Sangnier S, et al. Force-velocity profile: Imbalance determination and effect on lower limb ballistic performance. Int J Sports Med 35: 505–510, 2013.

30. Sheppard JM, Doyle TL, Taylor K. A methodological and performance comparison of free weight and smith-machine jump squats. J Aus Strength Cond 16: 5–9, 2008.

31. Simpson A, Waldron M, Cushion E, Tallent J. Optimised force-velocity training during pre-season enhances physical performance in professional rugby league players. J Sports Sci 39: 91–100, 2021.

32. Stone MH, O'Bryant HS, McCoy L, et al. Power and maximum strength relationships during performance of dynamic and static weighted jumps. J Strength Cond Res 17: 140–147, 2003.

33. Tufano JJ, Conlon JA, Nimphius S, et al. Cluster sets: Permitting greater mechanical stress without decreasing relative velocity. Int J Sports Physiol Perform 12: 463–469, 2017.

34. Valenzuela PL, Sánchez-Martínez G, Torrontegi E, et al. Should we base training prescription on the force-velocity profile? Exploratory study of its between-day reliability and differences between methods. Int J Sports Physiol Perform 16: 1001–1007, 2021.

35. Weakley J, Mann B, Banyard H, et al. Velocity-based training: From theory to application. Strength Cond J 43: 31–49, 2021.

36. Weakley J, Morrison M, García-Ramos A, et al. The validity and reliability of commercially available resistance training monitoring devices: A systematic review. Sports Med 51: 443–502, 2021.

37. Westgard JO, Hunt MR. Use and interpretation of common statistical tests in method-comparison studies. Clin Chem 19: 49–57, 1973.