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CONCURRENT VALIDITY AND RELIABILITY OF THE LOAD-VELOCITY RELATIONSHIP TO PREDICT THE ONE-REPETITION MAXIMUM DURING THREE WEIGHTLIFTING DERIVATIVES

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Abstract:

The study investigated the concurrent validity and reliability of the load-velocity relationship to predict the one-repetition maximum (1RM) of the power clean from the knee (PCK), high pull from the knee (HPK), and mid-thigh clean pull (MTCP). For each exercise, 12 participants performed two 1RM sessions tests and two sessions to measure the barbell's load-velocity relationship at 30, 45, 60, 75, and 90% of 1RM. The velocity recorded at each load was used to establish the linear regression equation and, consequently, to predict 1RM value. A low validity between the 1RM direct test and predicted 1RM was observed for PCK (typical error [TE]=3.96 to 4.50 kg, coefficient of variation [CV]=4.68 to 5.27%, effect size [ES]=-0.76 to -0.58, Bland-Altman bias [BAB]=9.83 to 11.19 kg), HPK (TE=4.58 to 5.82 kg, CV=6.44 to 8.14%, ES=-0.40 to -0.39, BAB=3.52 to 4.17 kg), and MTCP (TE=6.33 to 8.08 kg, CV=4.78 to 6.16%, ES=-0.29 to -0.19, BAB=3.98 to 6.17 kg). Adequate reliability was observed for the 1RM direct test and for the predicted 1RM. However, based on Bland-Altman limits of agreement, lower measurement errors were obtained for the 1RM direct test in comparison to the predicted 1RM for all the exercises. In conclusion, the load-velocity relationship was not able to predict 1RM values with high accuracy in the PCK, HPK, and MTCP. Moreover, the 1RM direct test was the most reliable for PCK, HPK and MTCP.

Key words: power clean, maximum strength, velocity-based training, measurement error, linear regression

Introduction

Weightlifting derivatives (i.e. exercises that omit a portion of the snatch or clean and jerk) allow substantial improvements in muscle power production and sport tasks such as vertical jumps, change of direction running, and sprint performances (Berton, Lixandrao, Pinto, & Tricoli, 2018; Suchomel, McKeever, & Comfort, 2020). For this reason, practitioners implement weightlifting derivatives in strength and conditioning programs as an appropriate tool to optimize sports performance (Suchomel, Comfort, & Stone, 2015).

In order to implement the weightlifting derivatives in strength and power-oriented training program, the procedure to determine adequate

loads is a recurrent question that remains as a potential practical barrier. Typically, the training load for weightlifting derivatives with the catch phase (weightlifting catching derivatives) or without catch phase (weightlifting pulling derivatives) is prescribed based on percentages of the one-repetition maximum test (1RM) of a weightlifting catching derivative (Comfort, Jones, & Udall, 2015; Suchomel & Sole, 2017). The 1RM test measures the maximum load that an individual can lift for one repetition and is considered the gold standard for assessing the maximal strength during dynamic tasks (Brown & Weir, 2001; Buckner, et al., 2017). However, the 1RM test has the disadvantage of being very time-consuming, at least in a large group of individuals (e.g. team sports) (Chapman,

Whitehead, & Binkert, 1998). Indeed, it has been reported that 1RM testing for a single exercise can take hours depending on the personnel involved and the number of available stations (Chapman, et al., 1998). Moreover, another disadvantage linked to the 1RM test is the injury risk (Niewiadomski, et al., 2008). It has been suggested that when performed incorrectly, the 1RM test might expose the athletes to a higher risk of injuries due to the heavy loads lifted (Niewiadomski, et al., 2008). As observed, the 1RM test has some disadvantages in certain contexts. Consequently, researchers have suggested that applicable practical alternatives might be used to predict the 1RM performance.

There has been great interest in determining 1RM performance based upon the load-velocity relationships (Banyard, Nosaka, & Haff, 2017; McMaster, Gill, Cronin, & McGuigan, 2014). In summary, velocity of the bar is measured at different submaximal loads through the load-velocity continuum and then a linear regression equation may be applied to explain the load-velocity relationships (Banyard, et al., 2017; Garcia-Ramos, et al., 2018a; Loturco, et al., 2017; Loturco, et al., 2016; Ruf, Chery, & Taylor, 2018). Furthermore, researchers suggested once the regression equation was determined for a given exercise, the 1RM value of that exercise may be estimated with as little as velocity of the first repetition (Loturco, et al., 2017). The use of the load-velocity relationship for predicting the 1RM performance was justified with high validity and reliability values obtained during the bench press and half-squat (Garcia-Ramos, et al., 2018a; Loturco, et al., 2016, 2017; Perez-Castilla, Garcia-Ramos, Padial, Morales-Artacho, & Feriche, 2018). For example, Loturco et al. (2017) reported a high validity of the load-velocity relationship to predict the 1RM performance during the bench press ($\geq 95\%$ of accuracy). Loturco et al. (2016) and Perez-Castilla et al. (2018) also reported similar results ($\geq 94\%$ of accuracy) during the half-squat. Regarding reliability, Garcia-Ramos et al. (2018a) have demonstrated the load-velocity relationship for predicting the 1RM performance in the bench press has a low measurement error (intraclass correlation coefficient [ICC] between 0.90 and 0.95, and coefficient of variation [CV] between 3.05% and 5.11%). Similarly, Banyard et al. (2017) reported a low measurement error of the load-velocity relationship for predicting the 1RM performance during the squat (ICC=0.92, CV=5.7% and standard error of the measurement [SEM]=8.6 kg).

Given the factors presented previously, it may be suggested the use of the load-velocity relationships to predict the 1RM values in the weightlifting derivatives (Haff, Garcia-Ramos, & James, 2020; Thompson, Rogerson, Dorrell, Ruddock, & Barnes, 2020; Thompson, Rogerson, Ruddock, Banyard, & Barnes, 2021). However, it is important to note that

linear regression equations and, consequently, their validity and reliability are specific for each exercise (Perez-Castilla, et al., 2018). Thus, the results found in the bench press and half-squat cannot be extrapolated to the weightlifting derivatives (Perez-Castilla, et al., 2018). Also, studies focused on predicting 1RM in weightlifting derivatives are scarce (Haff, et al., 2020). Therefore, the purpose of the present study was to investigate the concurrent validity and reliability of the load-velocity relationship to predict the 1RM value during the weightlifting derivatives power clean from the knee (PCK), high pull from the knee (HPK), and mid-thigh clean pull (MTCP). It is hypothesized that the load-velocity relationship would present a high degree of validity and reliability for all the exercises.

Methods

Participants

Twelve healthy male participants were recruited for this study (age 28.5 ± 5.2 years, body mass [BM] 80.3 ± 8.3 kg, body height 1.76 ± 0.05 m). They had at least one year of experience in weightlifting training (average: 3.2 ± 2.0 years, range: 1-7 years), and an average of 1RM to BM ratio in the PCK of 1.1 ± 0.1 kg·kg⁻¹ (range: 0.9 to 1.5 kg·kg⁻¹). All participants were informed about the purpose and all the potential risks of the study before signing a consent form. The protocol and consent were approved by the Ethics Committee of the University São Paulo (No. 90499718.7.0000.5391; approval date: July 7, 2018), and they complied with all ethical standards for research involving human participants set by the Declaration of Helsinki.

Procedure

This study investigated the concurrent validity and reliability of the load-velocity relationship for predicting the 1RM performance of the PCK, HPK, and MTCP. The 1RM direct test of each exercise (PCK, HPK, and MTCP) was selected as the criterion method to assess maximum performances for their respective comparisons. An individualized linear regression equation of the peak vertical barbell-velocity for the five submaximal loads (30, 45, 60, 75 and 90% of 1RM) was developed to predict the 1RM value for the PCK, HPK and MTCP. Thereafter, the predicted peak vertical barbell-velocity at 100% was used to estimate the 1RM value. The 1RM direct and 1RM predicted tests were performed on two occasions to determine the between-session reliability of each test, separately. Participants visited the laboratory on 12 occasions; four sessions per exercise. For a given exercise, the first two sessions were dedicated to the 1RM direct tests, while the test to predict the 1RM based on the load-velocity relationship was carried

out in the last two sessions. A battery of five loads (30, 45, 60, 75 and 90% of 1RM) was employed through the load-velocity continuum to establish a linear regression equation to predict the 100% of 1RM. Consistent intervals of 72 or 96 hours for each participant were granted between the sessions. The order of the exercises was randomized among all participants to minimize biases.

The 1RM direct test

The 1RM direct test was assessed for the PCK, HPK and MTCP weightlifting derivatives. For all the exercises, the participants performed a general warm-up on a cycle ergometer at 20 km·h⁻¹ for five minutes. After a one-minute rest interval, the participants performed a specific warm-up of the same weightlifting exercise that was randomly determined for that day (i.e. either PCK, or HPK, or MTCP). Similar to Suchomel, Wright, Kernozek, and Kline (2014) the specific warm-up consisted of three repetitions at 30, 50, and 70% followed by one repetition at 90% of their estimated 1RM. The estimation was determined by the information provided by the participants. Rest intervals of two minutes were provided between the loads. Three minutes after the specific warm-up, the 1RM test was performed. To determine the value of the 1RM, participants

had up to five attempts, with a three-minute rest interval between them, following previous guidelines (Brown & Weir, 2001). The 1RM value was defined as the highest load lifted for each exercise, through previously defined technical parameters (details in Table 1 and Figure 1) (DeWeese, Serrano, Scruggs, & Burton, 2013; Suchomel, DeWeese, & Serrano, 2016).

The 1RM predicted test

For all the exercises, a general and a specific warm-up were performed. The general warm-up was performed on a cycle ergometer at 20 km·h⁻¹ for five minutes. For the specific warm-up, the participants performed two sets of four repetitions at 45% of 1RM of the specific exercise (i.e. either PCK, or HPK, or MTP). Two minutes of rest were allowed between the sets.

Three minutes after the specific warm-up, participants randomly performed one of the three exercises (PCK, HPK or MTCP). The exercises were performed following the guidelines and procedures previously defined (Table 1 and Figure 1). To minimize biases related to the order of loads, all exercises were performed with a battery of loads in a randomized order. The loads analyzed were 30, 45, 60, 75 and 90% of 1RM. For loads

Table 1. Technical parameters to assess the 1RM performance of the power clean from the knee (PCK), high pull from the knee (HPK) and mid-thigh clean pull (MTCP)

Acceptable lifts	Unacceptable lifts
<p>PCK: In the start position, participants had the barbell supported on the blocks at a location of just above their knees (i.e. upper edge of the patella), with knees slightly bent, and hip flexed, shoulders above the bar, back flat, and arms extended with elbows pointed out (Figure 1B). Participants were asked to initiate the movement, and at mid-thigh position, to perform an explosive extension of the hips, knees, and ankles (triple extension) while concomitantly shrugging their shoulders in order to accelerate the barbell in a vertical motion. Then, participants were asked to catch the bar in the front rack position (shoulders rotated and flexed ahead with elbows up) underneath through a downward motion of their center of mass. Finally, participants were asked to complete the movement through a full extension of the hips and knees to reach the upright position with the barbell in the front rack position (Figure 1E).</p>	<p>The thighs of the participants were below parallel squat position to the floor in the instant of the catch.</p> <p>The participant was not able to complete the movement to an upright position with the barbell in the front rack (Figure 1E).</p>
<p>HPK: In the start position, participants followed the same procedures of the PCK (Figure 1C). However, during the HPK participants were asked to perform an explosive triple extension, and then to shrug shoulders straight up while flexing their elbows and pulling the barbell upward at the nipple line. In the final position (max barbell displacement) participants were in triple extension. An adjustment procedure for each participant was developed to ensure consistency in the displacement of the barbell between attempts (Figure 1F). Adjustment in displacement was performed with an empty barbell before the general warm-up of the 1RM direct test.</p>	<p>The participant did not cover the entire barbell displacement previously adjusted according to his/her anthropometric characteristics.</p> <p>During the upward phase, the barbell did not contact the elastic bands (Figure 1F) in both sides concomitantly.</p>
<p>MTCP: In the start position, participants were asked to keep the barbell supported on the blocks at mid-thigh position, with knees and hips slightly flexed, back upright, shoulders above the barbell and arms fully extended (Figure 1D). Then, participants were asked to perform an explosive triple extension in order to accelerate the barbell, while shrugging their shoulders with arms straight, elbows rotated out, and bar close to the body. Participants needed to complete the barbell displacement previously adjusted (i.e. from the position at mid-thigh from the blocks to the max barbell height achieved at the final point of the triple extension with shrugged shoulders). An adjustment procedure for each participant was developed to ensure consistency in the displacement of the barbell between attempts (Figure 1G). Adjustment in displacement was performed with an empty barbell before the general warm-up of the 1RM direct test.</p>	<p>The participant did not cover the entire barbell displacement previously adjusted according to his/her anthropometric characteristics.</p> <p>During the upward phase, the barbell did not contact the elastic bands (Figure 1G) in both sides concomitantly.</p>

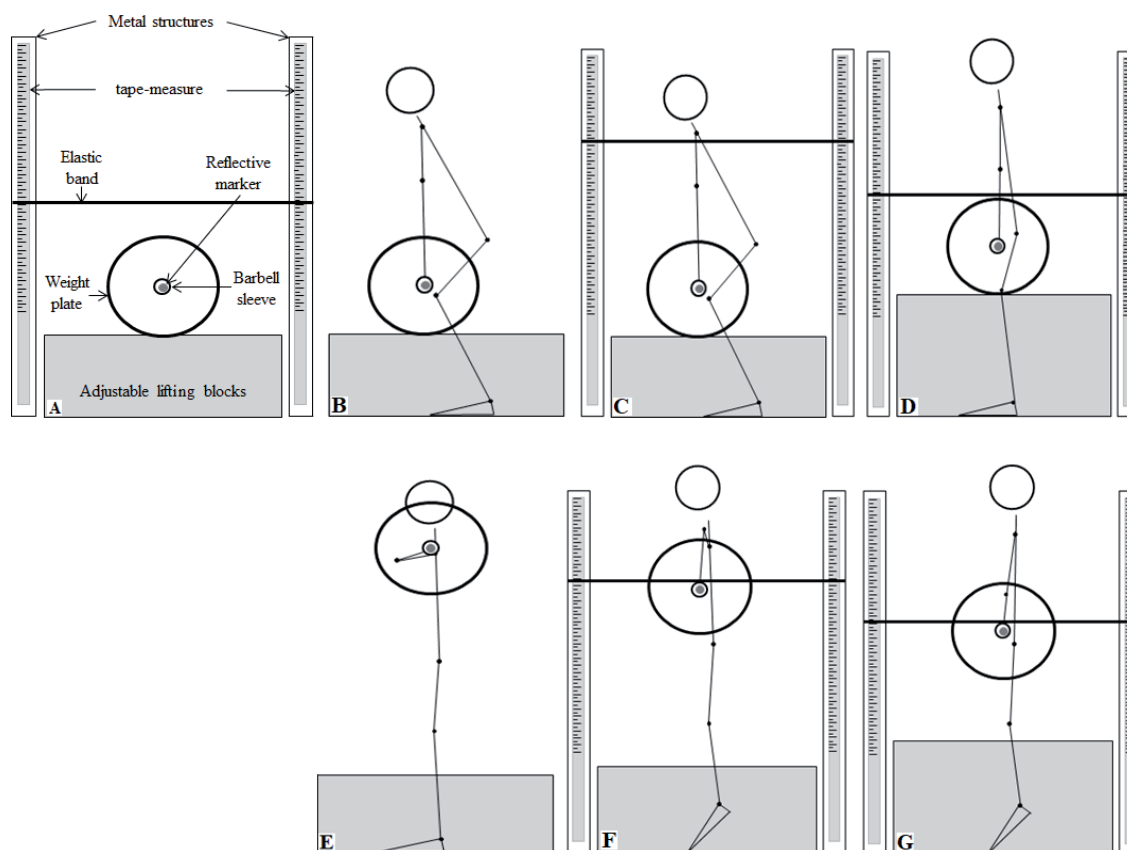


Figure 1. Adjustable metal structures positioned on each side of the barbell (A); starting position of the power clean from the knee (B), high pull from the knee (C), and mid-thigh clean pull (D). Final position of the power clean from the knee (E), high pull from the knee (F), and mid-thigh clean pull (G).

of 30, 45, 60, and 75% 1RM sets of three repetitions were performed, while at 90% 1RM only two repetitions were performed. The participants were instructed to perform all repetitions as fast as possible (Banyard, et al., 2017; Garcia-Ramos, et al., 2018a). A 30-second rest interval was allowed between the repetitions. Moreover, two-minute rest intervals were granted between the sets (Suchomel, et al., 2014).

Data collection

Video recordings of all the repetitions were obtained via an iPhone 5s camera (Apple Inc., USA) and were filmed with 1,280 x 720 pixel resolution at 120 frames per second (FPS) (Garhammer & Newton, 2013). Throughout all video recordings, the iPhone's camera was placed on a tripod 1.30 m above the ground, in the sagittal plane (participants' left side) at 5 m from the area in which the exercises were performed. A black background and a reflective marker placed on the left side of the Olympic barbell were used to allow better contrast and, consequently, accuracy in the auto-tracking of the barbell trajectory.

Barbell trajectory auto-tracking analyses were carried out by the Kinovea software (Experimental Version 0.8.25-x64) (Daehlin, Krosshaug, & Chiu,

2017; Garhammer & Newton, 2013). Kinovea is an appropriate option as it is easy-to-use, requires no experience to obtain accurate and reliable measurements, is a portable and free tool (i.e. can be used in real field context and have no cost), and has been used to assesses different sporting tasks (Balsalobre-Fernandez, Tejero-Gonzalez, del Campo-Vecino, & Bavaresco, 2014; Grigg, Haakonssen, Rathbone, Orr, & Keogh, 2018; Pueo, Penichet-Tomas, & Jimenez-Olmedo, 2020; Puig-Divi, et al., 2019). For the correct measurement, each video analysis was calibrated with the same reference length (weight plate of 45 cm diameter) and by the same investigator (Garhammer & Newton, 2013). After this step, an auto-tracking procedure was performed for all the repetitions. For all the exercises, the movement start was defined when the weight plates were resting on the blocks. It should be noted that for each participant, the height of the blocks was individually adjusted prior to the beginning of the testing session. The barbell was supported on the blocks to ensure the same vertical barbell displacement for all the repetitions and across the loads. However, the end of the movement differed between exercises. For the PCK, the end of the movement was defined as the first negative peak velocity that occurred after the start of the lift (Balsalobre-Fernandez, Geiser,

Krzyszowski, & Kipp, 2020), whereas for the HPK and MTCP the end was defined as the frame that barbell touched the elastic band (Figure 1). Finally, peak vertical barbell velocity was obtained from vertical axis (y-axis) in *.xlsx files for subsequent statistical analysis. Only the repetition with the highest peak vertical barbell velocity at each load was considered for statistical analysis. It is important to highlight that for concentric-only exercises the use of peak velocity is considered appropriate as it presents a similar result when compared to the mean velocity, or the mean propulsive velocity (Garcia-Ramos, Pestaña-Melero, Pérez-Castilla, Rojas, & Haff, 2018b).

Statistical analyses

All data are presented as mean±SD, where appropriate. Statistical analyses were carried out for each exercise separately. The first procedure applied was the Shapiro-Wilk's test to verify normal distribution. Then, the peak vertical barbell velocity was estimated at 1RM (100%) for each participant. We then performed an individualized linear regression equation (Thompson, et al., 2021) between the peak vertical barbell velocity and each of the five submaximal loads (30, 45, 60, 75 and 90% of 1RM). Thereafter, a second linear regression was carried out to predict the 1RM estimate. The peak vertical barbell velocity value at 100% 1RM was used in the linear regression equation to predict the 1RM value. In addition, the linear regression equation to predict the 1RM value was assessed by the coefficient of determination (R^2) and p-value. The significance level was set at $p \leq 0.05$.

To determine validity, the best performance of the two 1RM direct tests was compared to the predicted 1RM test of sessions 1 and 2. Validity was assessed with typical error (TE), coefficient of variation (CV) (Hopkins, 2000), Hedges' g effect size (ES) and the associated 95% confidence intervals (CI) (Nakagawa & Cuthill, 2007). ESs were interpreted as: trivial (0 to <0.2), small (0.2 to <0.6), moderate (0.6 to <1.1) and large (1.2 to 2.0) based on previous guidelines (Hopkins, Marshall, Batterham, & Hanin, 2009). However, if the CI overlapped thresholds for substantial positive and negative values, the effect was considered unclear (Nakagawa & Cuthill, 2007). In addition, Bland-Altman plots (limits of agreement at 95% and bias) were used to evaluate the agreement of the 1RM value between the 1RM direct test (best performance) and the two predicted tests (session 1 and session 2) (Bland & Altman, 1986).

Between-sessions reliability was evaluated for the 1RM direct and predicted tests separately. For that, the two-way mixed method intraclass correlation coefficient (ICC) and associated 95% CI were

calculated. The ICC was interpreted based on the recommendations of Koo and Li (2016), where less than 0.50, between 0.50 and 0.75, between 0.75 and 0.90, and greater than 0.90 indicated as poor, moderate, good, and excellent reliability, respectively. In addition, TE and CV (Hopkins, 2000), ES and the associated 95% CI (Nakagawa & Cuthill, 2007), and Bland-Altman plots (limits of agreement at 95% and bias) were also utilized (Bland & Altman, 1986).

Finally, a *post-hoc* power analysis using G*Power version 3.1.9.7 software was performed to determine the present study's statistical power. The *post-hoc* analysis was calculated for each linear equation that predicted 1RM value for PCK, HPK, and MTCP. The input parameters were the R^2 of each linear equation, ES f^2 , an alpha level of 0.05, total sample size, and the number of predictors.

Results

The Shapiro-Wilk's test of normality revealed all data were normally distributed ($p > 0.05$). The estimated peak vertical barbell velocity at 100% for the PCK was $1.93 \pm 0.12 \text{ m}\cdot\text{s}^{-1}$ for session 1 and $1.84 \pm 0.16 \text{ m}\cdot\text{s}^{-1}$ for session 2. For the HPK, the estimated peak vertical barbell velocities at 100% were $2.08 \pm 0.19 \text{ m}\cdot\text{s}^{-1}$ and $2.17 \pm 0.22 \text{ m}\cdot\text{s}^{-1}$ for sessions 1 and 2, respectively. Finally, during the MTCP the estimated peak vertical barbell velocities at 100% were $0.74 \pm 0.20 \text{ m}\cdot\text{s}^{-1}$ and $0.70 \pm 0.13 \text{ m}\cdot\text{s}^{-1}$ for sessions 1 and 2, respectively. A second linear regression equation was carried out between all peak vertical barbell velocities and their respective loads. The R^2 were 0.60 ($p < 0.001$) and 0.66 ($p < 0.001$) for the PCK, 0.87 ($p < 0.001$) and 0.82 ($p < 0.001$) for the HPK, and 0.84 ($p < 0.001$) and 0.91 ($p < 0.001$) for the MTCP for sessions 1 and 2, respectively (Figure 2).

For validity, the load-velocity relationship underestimated 1RM values when compared with the 1RM direct test. For the PCK, the best 1RM direct test was $90.42 \pm 16.34 \text{ kg}$, whereas lower values were observed for the estimated 1RM test of sessions 1 ($78.51 \pm 14.83 \text{ kg}$) and 2 (80.57 ± 17.39). For the HPK, the best 1RM direct test was $73.27 \pm 9.56 \text{ kg}$, whereas lower values were observed for the estimated 1RM test of sessions 1 ($69.74 \pm 7.94 \text{ kg}$) and 2 (69.10 ± 11.73). Finally, the best 1RM direct test in the MTCP was $134.40 \pm 21.32 \text{ kg}$, whereas lower values were observed for the estimated 1RM test of sessions 1 and 2 (127.68 ± 24.13 and 130.41 ± 20.86 , respectively). The results of the validity analysis are presented in Table 2 (TE, CV, and ES) and Figure 3 (limits of agreement at 95%, and bias).

For reliability, the results are presented in Table 3 and Figure 4. For the PCK, HPK, and MTCP higher reliability was found for the 1RM direct test compared to the estimated 1RM test.

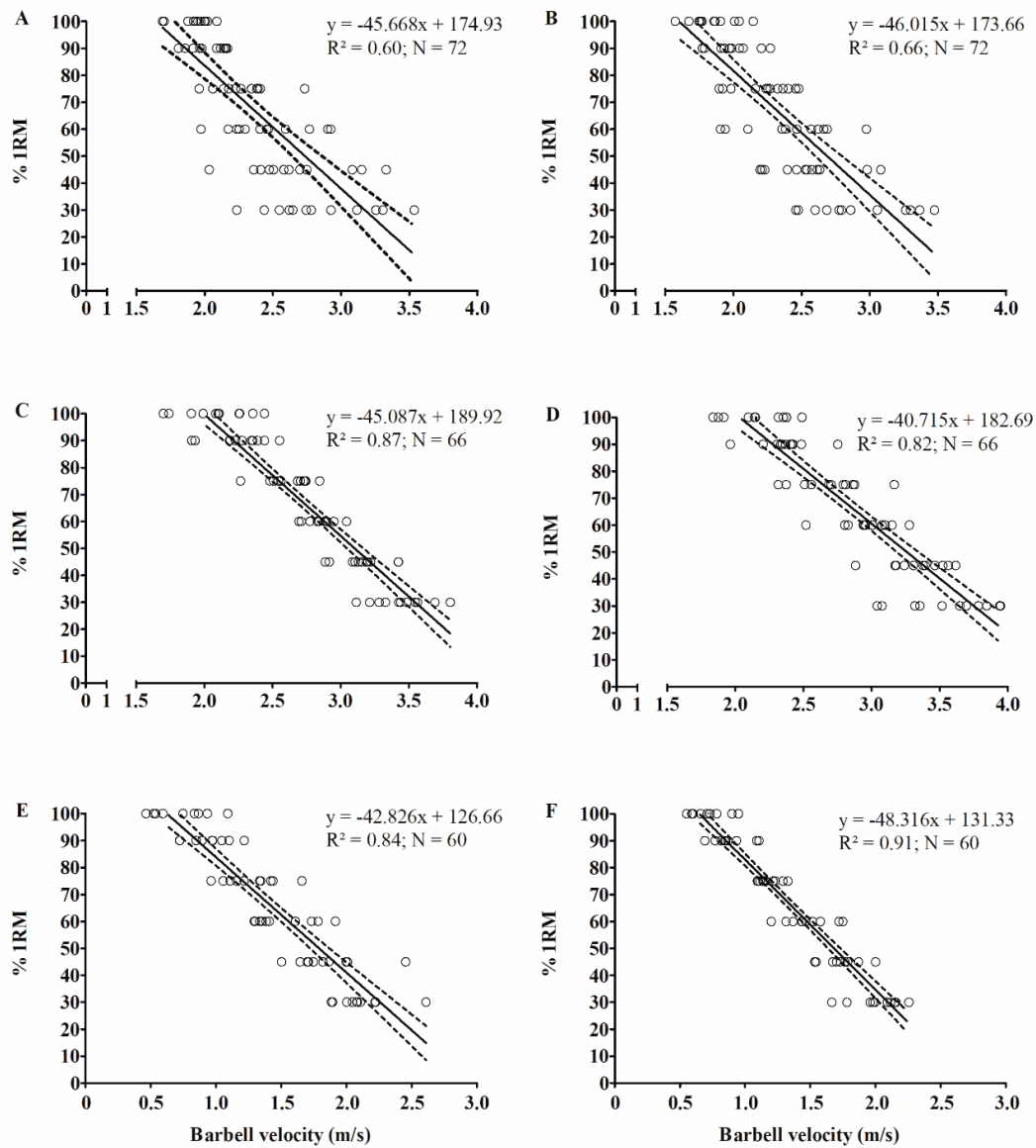


Figure 2. Relationship between barbell-velocity and percentages of IRM (loads 30, 45, 60, 75, 90 and 100% IRM). (A) PCK session 1, (B) PCK session 2, (C) HPK session 1, (D) HPK session 2, (E) MTCP session 1, and (F) MTCP session 2. Dotted lines represent confidence interval (95%). R2=coefficient of determination; N=number of raw data included in the regression analysis.

Table 2. Validity between the best IRM direct test vs. predicted IRM – session 1, and best IRM direct test vs. predicted IRM – session 2 of the exercises power clean from the knee (PCK), high pull from the knee (HPK) and mid-thigh clean pull (MTCP)

	Best 1RM direct test vs. predicted 1RM – Session 1	Best 1RM direct test vs. predicted 1RM – Session 2
PCK		
TE (kg)	3.96 (2.81, 6.72)	4.50 (3.19, 7.66)
CV (%)	4.68 (3.30, 7.90)	5.27 (3.70, 8.90)
ES	-0.76 (-1.27, -0.31)	-0.58 (-1.06, -0.15)
HPK		
TE (kg)	5.82 (4.07, 10.22)	4.58 (3.21, 8.05)
CV (%)	8.14 (5.80, 10.00)	6.44 (4.60, 11.00)
ES	-0.40 (-0.53, 0.35)	-0.39 (-0.53, 0.34)
MTCP		
TE (kg)	8.08 (5.56, 14.76)	6.33 (4.36, 11.57)
CV (%)	6.16 (4.30, 11.00)	4.78 (3.30, 8.40)
ES	-0.29 (-0.53, 0.39)	-0.19 (-0.51, 0.41)

Note. TE=typical error, CV=coefficient of variation, ES=Hedges' g effect size. Data are presented as mean and confidence interval 95%.

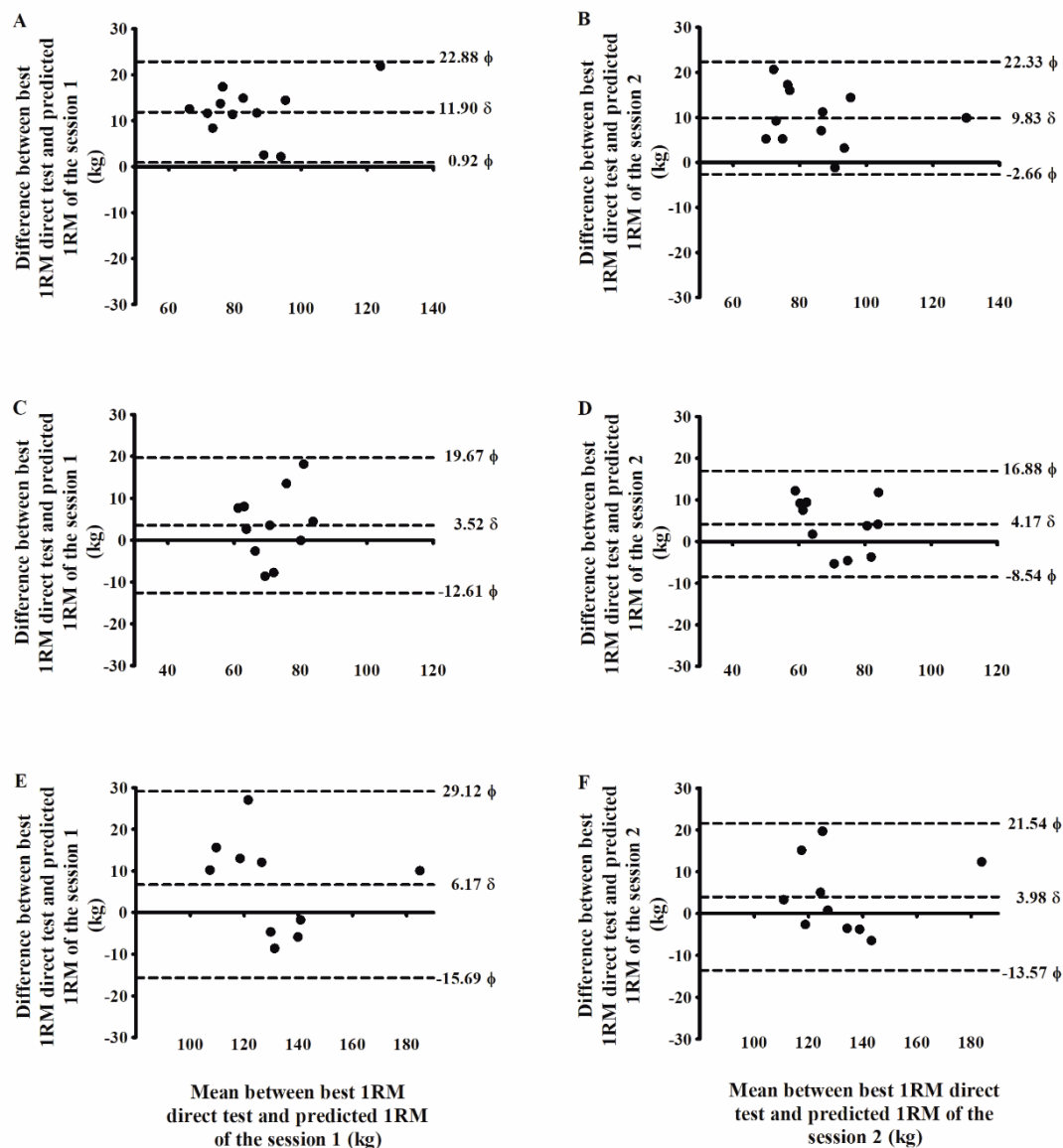


Figure 3. Validity analysis. Bland-Altman plots showing differences between (A) best IRM direct test vs. predicted IRM – session 1, and (B) best IRM direct test vs. predicted IRM – session 2 for PCK; (C) best IRM direct test vs. predicted IRM – session 1, and (D) best IRM direct test vs. predicted IRM – session 2 for HPK; (E) best IRM direct test vs. predicted IRM – session 1, and (F) best IRM direct test vs. predicted IRM – session 2 for MTCP. δ =bias; θ =superior and inferior limits of agreement.

Table 3. Reliability between IRM direct test and predicted IRM based on the load-velocity relationship

Tests	Session 1 (kg)	Session 2 (kg)	ICC	TE (kg)	CV (%)	ES
PCK						
1RM direct test	89.33 ± 16.62	88.91 ± 16.85	0.97 (0.89 - 0.99)	3.04 (2.15 - 5.16)	3.41 (2.40 - 5.80)	-0.02 (-0.44 - 0.39)
Predicted 1RM	78.51 ± 14.83	80.57 ± 17.39	0.97 (0.83 - 0.99)	3.84 (2.72 - 6.52)	4.82 (3.40 - 8.20)	0.13 (-0.29 - 0.55)
HPK						
1RM direct test	71.18 ± 8.22	72.68 ± 9.68	0.91 (0.64 - 0.98)	2.58 (1.81 - 4.54)	3.59 (2.50 - 6.30)	0.17 (-0.27 - 0.61)
Predicted 1RM	69.74 ± 7.94	69.10 ± 11.73	0.73 (0.25 - 0.93)	5.26 (3.68 - 9.24)	7.58 (5.40 - 13.00)	-0.06 (-0.51 - 0.37)
MTCP						
1RM direct test	133.00 ± 21.78	133.90 ± 21.55	0.98 (0.95 - 0.99)	1.86 (1.28 - 3.40)	1.39 (0.97 - 2.40)	0.04 (-0.40 - 0.48)
Predicted 1RM	127.68 ± 24.13	130.41 ± 20.86	0.95 (0.73 - 0.99)	6.90 (4.75 - 12.60)	5.34 (3.70 - 9.40)	0.12 (-0.34 - 0.59)

Note. PCK=power clean from the knee, HPK=high pull from the knee, MTCP=mid-thigh clean pull.

ICC=intraclass correlation coefficient, TE=typical error, CV=coefficient of variation, and ES=Hedges' g effect size (data are presented as mean and confidence interval 95%). Sessions 1 and 2=data are presented as mean and standard deviation.

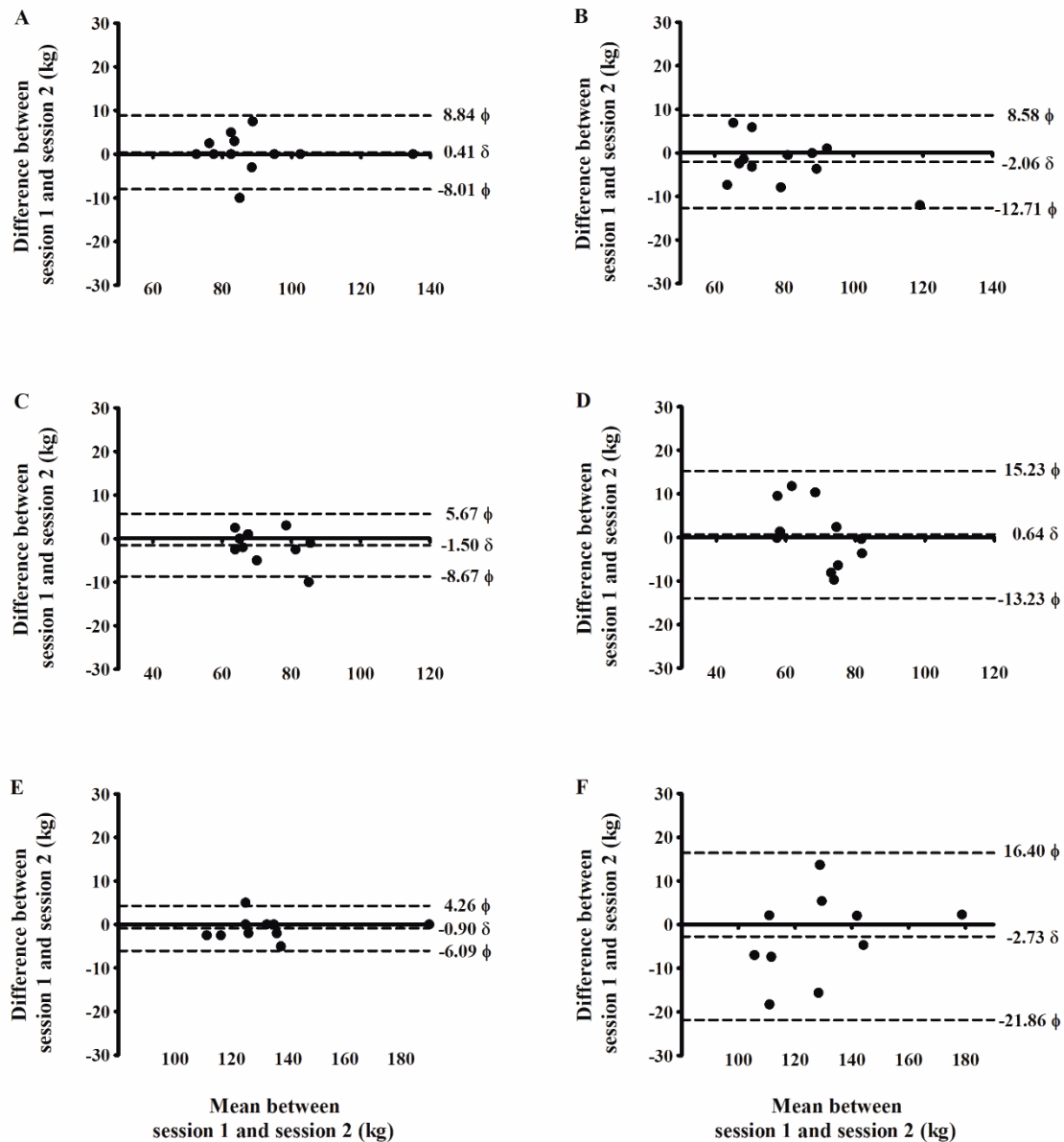


Figure 4. Reliability analysis. Bland-Altman plots showing differences between (A) IRM direct test – sessions 1 and 2, and (B) predicted IRM – sessions 1 and 2 for PCK; (C) IRM direct test – sessions 1 and 2, and (D) predicted IRM – sessions 1 and 2 for HPK; (E) IRM direct test – sessions 1 and 2, and (F) predicted IRM – sessions 1 and 2 for MTCP. δ =bias, θ =superior and inferior limits of agreement.

Discussion and conclusions

The purpose of this study was to investigate the concurrent validity and reliability of the load-velocity relationship to predict IRM values in the PCK, HPK and MTCP. It was hypothesized that for all the exercises the load-velocity relationships would present high validity and reliability. However, the main finding of this study is that the load-velocity relationship is not a suitable method to predict the IRM performance accurately during the PCK, HPK and MTCP. In addition, although the IRM predictions based on the load-velocity relationship demonstrated high reliability for the three exercises, better reliability and lower measurement errors were reported for the IRM direct test during the three exercises.

In the present study, the linearity of the load-velocity relationship was lower for PCK in both IRM prediction sessions ($R^2=0.60$ and 0.66), compared to HPK ($R^2=0.82$ and 0.87) and MTCP ($R^2=0.84$ and 0.91) (Figure 2). Although greater linearity of the load-velocity relationship was observed for the HPK and MTCP, the results of the three exercises did not corroborate previous findings in the literature. Strong linearity ($R^2 \geq 0.94$) in the load-velocity relationship was reported for the bench press and half-squat exercises in previous research (Loturco, et al., 2016, 2017; Perez-Castilla, et al., 2018). These differences may be attributable to technical parameters, in which the load-velocity relationship has proven to be task-specific (Perez-Castilla, et al., 2018). Nonetheless, the explanation

for the different results between our study and the literature is not entirely clear and more research is warranted.

Strong linearity for the load-velocity relationship is necessary for an accurate prediction of the 1RM value (Garcia-Ramos, et al., 2018a). As aforementioned, our results did not demonstrate strong linearity based on R^2 values (0.60 to 0.91) (Figure 2). In this sense, a poor validity of the load-velocity relationship was observed (Table 2 and Figure 3). In this study, the predicted 1RM values were underestimated in sessions 1 and 2 when compared to the 1RM direct tests of the three weightlifting derivatives. Researchers reported results support the low accuracy of the load-velocity relationship to predict the 1RM value in some exercises. For instance, Ruf et al. (2018) showed that the load-velocity relationship overestimated the estimated 1RM value compared to the 1RM direct test for the deadlift. Similarly, Banyard et al. (2017) reported large absolute errors (10.6 to 17.2 kg) and poor CVs (7.4 to 12.8%) between the estimated 1RM value and the 1RM direct test for the back squat. In contrast, Loturco et al. (2016, 2017) demonstrated low CV between the estimated 1RM value and the 1RM direct test for the half-squat (0.30 to 0.75%) and bench press exercises (1.12 to 1.15%), respectively. In addition, Garcia-Ramos et al. (2018a) demonstrated low systematic bias between the predicted 1RM and the 1RM actual test (-2.3 to 0.5 kg) for the bench press exercise. Therefore, the load-velocity relationship seems to be an adequate option for predicting the 1RM value. As noted, the accuracy of the load-velocity relationship to predict the 1RM value may vary based on the exercise. For the three weightlifting derivatives (PCK, HPK, and MTCP) evaluated in this study, the use of the load-velocity relationship to predict the 1RM value is not recommended.

The analyses showed an acceptable reliability and low validity of the predicted 1RM values for the three weightlifting derivatives. However, whether the reliability of the 1RM value predicted by the load-velocity relationship was considered adequate, better results were found for the 1RM direct test (Table 3 and Figure 4). These results are in line with previous research (Banyard, et al., 2017; Garcia-Ramos, et al., 2018a). For example, Banyard et al. (2017) reported small absolute errors (2.9 kg) and good CVs (2.1%) for the 1RM direct test during the back squat exercise, while moderate to large absolute errors (8.6 to 16.8 kg) and poor CVs (5.7 to 12.2%) for the estimated 1RM value. Similarly, Garcia-Ramos et al. (2018a) showed better reliability

for the bench press 1RM direct test (CV = 1.97%) compared to the predicted 1RM value (CV = 3.8 to 5.1%). In this study, the higher reliability of the 1RM direct test may be evidenced through the difference in the width of limits of agreement of the Bland-Altman plots (Figure 4). For example, the PCK limits of agreement for the 1RM direct test were between -8.01 to 8.89 kg, whereas an interval slightly higher was found for the predicted 1RM value (-12.7 to 8.58 kg). In contrast, substantial differences were observed in the limits of agreement for the HPK and MTCP. HPK limits of agreement were observed between -8.67 to 5.67 kg for the 1RM direct test and -13.23 to 15.23 kg for the predicted 1RM value. Similarly, MTCP limits of agreement were observed between -6.09 to 4.26 kg for the 1RM direct test, and -21.86 to 16.40 kg for the 1RM predicted value. In addition, only in the HPK was observed a higher ICC for the 1RM direct test (ICC=0.91) compared to the estimated 1RM value (ICC=0.73) (Table 3). Similarly, only for the MTCP lower TE and CV values were observed for the 1RM direct test compared to the estimated 1RM value (Table 3). Taken together, the 1RM direct test seems to be more reliable than the predicted 1RM values based on the load-velocity relationship.

Three limitations in the present study need to be acknowledged. First, in this study a kinematic approach using a high-speed camera (i.e. ≥ 240 frames per second) and three-dimensional motion capture (i.e. gold standard) was not performed (Lorenzetti, Lamparter, & Luthy, 2017; Pueo, 2016). Although it may be a limitation, from a practical standpoint, few coaches have access to this equipment. In this sense, the data collected by a smartphone and the use of a free software, may favor greater implementation and usability. Second, as noted only two sessions to predict the 1RM value was performed. Perhaps more testing sessions could improve the accuracy to predict the 1RM value. However, multiple testing sessions are impractical especially in professional teams with large rosters. Third, sample size of the present study was relatively small, and thus the generalization of the results should be performed with caution. Nevertheless, even with a small sample size, the *post-hoc* power analysis results demonstrated an adequate power (≥ 0.85) for all the exercises.

In conclusion, the load-velocity relationship showed low validity to predict the 1RM value for PCK, HPK and MTCP. Furthermore, these results have also demonstrated that although a high reliability of the predicted 1RM value may be expected, the 1RM direct test should be the preferred option.

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