

Examining strength, muscular power, and maximal performance in the power clean among CrossFit® practitioners

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Abstract:

Background: CrossFit® (CF) a globally embraced fitness program, has gained widespread popularity for its comprehensive approach to improving overall fitness. Central to its methodology is the emphasis on enhancing various physical attributes, including strength and muscular power. The power clean (PC), an integral exercise within CF, serves as an important tool for assessing the muscular strength profile. **Aim:** This study aimed to investigate the intricate relationship between muscle strength, power variables, and maximal performance in executing the PC, an Olympic Weightlifting exercise, among CF practitioners. **Material and methods:** Thirty-five recreationally trained men, with an average age of 31 ± 5.2 years and a body mass of 85.7 ± 13.6 kg, actively participated in the study. The assessment of muscular strength involved key measures such as the isometric mid-thigh pull (IMTP) test, countermovement vertical jump (CMJ), and relative 1-RM progressive test specifically tailored for the PC exercise. **Results:** Our findings found significant correlations between the indices of strength, muscle power and load in PC. The variables exhibiting the highest correlations with 1-RM in the PC were maximal dynamic strength ($F_{\max(\text{dyn})}$) ($R=0.76$), maximal power ($P_{\max}$) ($R=0.71$), and maximal isometric strength ($F_{\max(\text{iso})}$) ($R=0.51$). However, lower limbs power output (LLP) ($R=0.42$) was very low predictive value and RFD presented trivial and small correlation values without statistical significance. **Conclusion:** We conclude that $F_{\max(\text{dyn})}$ and $P_{\max}$ have a greater capacity to estimate 1-RM in the PC exercise in CF practitioners. $F_{\max(\text{iso})}$ and LLP had a lower predictive capacity, certainly because they are not evaluated during PC movement. The RFD, despite being important, showed trivial-low predictive capacity, certainly because it was measured during the IMTP test. Further studies with other OW exercises may provide more detailed information about the relationship between strength variables and the execution of these movements.

Key Words: High-Intensity Interval Training, Conditioning, Athletic Performance, Neuromuscular Assessment.

Introduction

CrossFit® (CF) is a conditioning program featuring short-duration, high-intensity exercises rooted in calisthenics, gymnastics, bodyweight strength training, and Olympic Weightlifting (OW) exercises (Carreker & Grosicki, 2020). Sessions are structured with mobility and warm-up exercises, followed by technical enhancement exercises (skills) and the main part known as the workout of the day (WOD) (Meier et al., 2023).

Performance in specific WODs (benchmarks) and tests (Personal Records; PR) is used to monitor the individual progress of participants. From a fitness standpoint, CF aims for the simultaneous improvement of various components such as muscular strength, power, cardiorespiratory fitness, and subsequently, alterations in body composition components (Feito et al., 2018).

It should be noted that today CF gains steady popularity (Petrova et al., 2022). There exist CF competitions at local, regional, national, and international levels, where outcomes have been associated with different physical variables (Carreker & Grosicki, 2020). Common variables include maximal oxygen uptake, maximal anaerobic power output, strength, and power of upper and lower limbs, as well as body composition. These variables have demonstrated different capacities in explaining athletes' performance in competitions (Martínez-Gómez et al., 2020). This is due to the unpredictability and variation in selected exercises, leading to distinct structures like a predetermined number of repetitions/rounds to be completed in the shortest time possible (Rounds for Time; RFT), or participants attempting the highest number of repetitions/rounds within a stipulated time (AMRAP) (Mangine et al., 2020).

Olympic Weightlifting (OW) exercises are part of the daily and competitive routine of CF (Maté-Muñoz et al., 2017) and have been incorporated into the training regimes of various sports disciplines to improve strength (Suchomel et al., 2020). Performance in these exercises depends on technique, strength, and muscular power (Brady et al., 2020). Consequently, the ability to optimize muscular strength is considered fundamental for successful performance in CF and other athletic and sporting activities.

For assessing strength components in OW, maximal isometric strength and the rate of force development (RFD) are common variables (Beckham et al., 2018). The most common test for evaluating RFD is the isometric mid-thigh pull (IMTP) test (Dos Santos et al., 2018) (Stone et al., 2019). The position in this test which is supposed to mimic the second pull of the Power Clean (PC) (Lum et al., 2020), where the highest force (Moreira et al., 2023) and speed (Santos et al., 2020) are generated.

The PC is a foundational exercise among several other full-body exercises in OW, resulting from the combined extension of the ankle, knee, and hip joints. It is commonly used in physical preparation due to its similarity with specific sports movements when the intention is to apply maximal force in a brief time. Recent studies have indicated that strength performance in OW exercises has a strong correlation with final rankings in CF competitions (Peña et al., 2021). However, few studies have analyzed the relationship between strength and power variables in OW exercises among CF practitioners. A study (Mangine et al., 2020) examined the differences between advanced and recreational CF practitioners compared to a physically active group. The authors reported that advanced practitioners exhibited higher maximal strength and greater RFD compared to the physically active group. Martínez-Gómez et al (2019) explored the relationship between power and muscular strength measured in the full squat exercise. The findings show moderate to strong correlations between peak power and performance in different WODs.

Therefore, few studies have explored the ability to predict one repetition maximum (1-RM) through lower limb power and isometric strength in PC exercise. Through a recent systematic review (Lum et al., 2020) it is possible to see that the correlation values between 1-RM and lower limb power or isometric strength can change predictive capabilities in relation to different competitive levels. However, none of the studies presented in this review explored these relationships in CF practitioners.

To date, the authors are not aware of any study that has established a relationship between 1-RM in the PC and various strength variables in CF practitioners. Therefore, this study aimed to investigate the intricate relationship between muscle strength, power variables, and maximal performance in executing the PC, an Olympic Weightlifting exercise, among CF practitioners. Insights from muscle strength derivations can provide information about fitness, as power training depends on the force/velocity relationship. Such findings may assist coaches and physical trainers in the appropriate prescription and control of power training.

Material & methods

Experimental Approach to the Problem

In this study, 35 male recreational CF participants were evaluated, with an average age of 31 ± 5.2 years, body mass of 85.7 ± 13.6 kg, and training experience of 38.9 ± 19.2 months. Participants were regularly training in CF and demonstrated a strength level ranging from intermediate to advanced, as per the Weightlifting Strength Standards (<https://strengthlevel.com/>), which categorizes individuals based on their body mass and the load lifted in PC. General warm-up and technical analysis during this movement were overseen by a CF-accredited coach (Level 1).

Tests were conducted in the morning, in the following order: countermovement jump (CMJ), IMTP, and a progressive test up to 1-RM in PC. A five-minute rest was allowed between each test to prevent interference from one test to another. A standard warm-up was performed before the tests, consisting of a five-minute cycle on an ergometer at a cadence of 50 rpm, followed by dynamic stretching exercises and barbell lifts (20 kg) for five minutes, supervised by the coach. Participants, after being informed about the investigation's

objectives and the procedures they would undergo, voluntarily agreed to participate in the study and signed an informed consent form by the norms of Resolution 196/96 of the National Health Council concerning research involving human beings. The local Research Ethics Committee approved the procedures, under number 3.290.772.

Lower limb power output

Participants were familiarized with the movement by performing 6 to 10 submaximal jumps and were instructed to keep their hands fixed on their waist, both at the beginning and the end of the jump, with their feet on the contact mat, and to keep their knees extended during the jump's airborne phase. Participants were instructed to jump as high as possible and to land with both feet simultaneously. Each participant completed six jumps, with a 30-second rest between each jump. A contact mat was used to determine flight time and calculate lower limb power (Jump System Pro Cefise[®]). Lower limb power was estimated from the product of the participant's weight and take-off velocity (Banja et al., 2023). Take-off velocity was estimated from flight time (t) and gravity (g) using the equation $(gt/2)$. As this study measured maximal capacities, the jump with the highest relative power was used for analysis.

Isometric mid-thigh pull test

Participants were positioned in front of a handle and pulled upwards. The handle was connected to a load cell that recorded the force. They familiarized themselves with the movement by pulling three times with less than maximal force to adjust their body position. Each participant made three 5-second attempts with a 3-minute rest in between. They were instructed to pull the handle as "firmly and quickly as possible," maintaining maximal effort. Participants were also instructed to maintain a knee angle between 90 and 120° during the test, which was monitored using a goniometer, with a full knee extension equating to 180°. Force data were recorded at a rate of 100 Hz using a load cell.

Time series were analyzed using DasyLab[®] version 11 software (National Instruments[®], Ireland). Force-time curves were filtered using a fourth-order 10 Hz low-pass Butterworth filter implemented in the software. Analyzed variables also included the RFD, calculated as the maximal slope on the force-time curve at 10-milliseconds (ms) time intervals; and the position of the force-time curve obtained at different times (50, 100, 150, 200, and 250 ms from the onset of force production) (Mangine et al., 2020). The analysis began when the force value increased by 5% compared to the static force without returning to these values. The attempt with the highest relative maximal force was used for analyses.

Progressive loading test

Maximal dynamic force ($F_{\max}(\text{Dyn})$) and maximal power ($P_{\max}$) (both during the concentric phase) and 1-RM load in the PC exercise were determined using a linear velocity transducer at a frequency of 100 Hz (PeakPower Cefise[®]) attached to the bar by an inelastic cord. Time series were analyzed using DasyLab[®] version 11 software (National Instruments[®], Ireland). Force-time curves were filtered using a fourth-order 10 Hz low-pass Butterworth filter implemented in the software.

Each participant performed an incremental test in the PC exercise up to 1-RM. The test began with a load of 40 kg. Participants executed one repetition in PC at maximal speed upon hearing the command. The load was progressively increased by 10 kg increments each attempt, as long as the peak bar velocity was equal to or greater than 1.5 m/s. When this value was less than 1.5 m/s, the load increment was reduced to 5 kg, and the rest periods were extended from 3 to 5 minutes (Maté-Muñoz et al., 2017). When necessary, the load was increased in increments of 1 to 2 kg until the participant could not lift the load with the correct technique. The highest load lifted was considered the 1-RM value. This load (in Kg) was multiplied by the acceleration of gravity (g) and normalized by body mass for each participant.

Statistical analyses

To verify data normality and homogeneity, Shapiro-Wilk and Levene tests were employed, respectively. Data underwent a descriptive statistical analysis using mean and standard deviation. The correlation between the previously described variables and the 1-RM value was calculated using the Pearson correlation coefficient, and Spearman's correlation was used when they did not show normal distribution. Correlation coefficients were interpreted using the following criteria: trivial ($0 \leq r < 0.1$); small ($0.2 \leq r < 0.3$); moderate ($0.3 \leq r < 0.5$); large/strong ($0.5 \leq r < 0.7$); very large/very strong ($0.7 \leq r < 0.9$); almost perfect ($0.9 \leq r < 1.0$); and perfect ($r = 1.0$). All analyses were performed in the Statistical Package for Social Sciences[®] (SPSS Inc. USA), v. 25.0, using a significance level of 5%.

Results

The results for the variables are shown in Table 1. The findings showed that $F_{\max}(\text{iso})$, $F_{\max}(\text{dyn})$, $P_{\max}$, and LLP are significantly correlated with 1-RM performance (Table 2).

Table 1. Strength and performance variables.

Variable	Mean $\pm$ Standard Deviation
1-RM (N. Kg ⁻¹)	11.1 $\pm$ 1.7
F _{max (iso)} (N. Kg ⁻¹)	13.2 $\pm$ 2.3
F _{max (dyn)} (N. Kg ⁻¹)	17.8 $\pm$ 3.9
P _{max} (W. Kg ⁻¹)	29.5 $\pm$ 6.5
RFD ₅₀ (N. s ⁻¹)	1532.3 $\pm$ 1315.1
RFD ₁₀₀ (N. s ⁻¹)	2537.2 $\pm$ 1760.3
RFD ₁₅₀ (N. s ⁻¹)	2942.8 $\pm$ 1580.7
RFD ₂₀₀ (N. s ⁻¹)	2848.6 $\pm$ 1181.1
RFD ₂₅₀ (N. s ⁻¹)	2582.2 $\pm$ 908.1
LLP (W. Kg ⁻¹)	50.3 $\pm$ 3.8

Legend: 1-RM= Maximal load at Power clean relative to body mass; F_{max (iso)} = Maximal isometric force; F_{max (dyn)}= Maximal dynamic force in the Power clean at 1-RM; P_{max}= Maximal power in Power clean at 1-RM; RFD₅₀ = Rate of force development at 50 milliseconds; RFD₁₀₀= Rate of force development at 100 milliseconds; RFD₁₅₀= Rate of force development at 150 milliseconds; RFD₂₀₀= rate of force development at 200 milliseconds; RFD₂₅₀= Rate of force development at 250 milliseconds; LLP= Lower limbs power output in counter movement jump.

Table 2: Correlation between variables and 1-RM on PC.

	1-RM	<i>p</i>
F _{max (iso)}	0.51 (^p)	0.001*
F _{max (Din)}	0.76 (^p)	0.001*
P _{max}	0.71 (^p)	0.001*
RFD ₅₀	0.27 (^s)	0.558
RFD ₁₀₀	0.20 (^s)	0.468
RFD ₁₅₀	0.16 (^p)	0.333
RFD ₂₀₀	0.17(^p)	0.340
RFD ₂₅₀	-0.05 (^p)	0.762
LLP	0.42 (^p)	0.016*

Legend: 1-RM= Maximal load at Power clean relative to body mass; F_{max (iso)} = Maximal isometric force; F_{max (dyn)}= Maximal dynamic force in the Power clean at 1-RM; P_{max}= Maximal power in Power clean at 1-RM; RFD₅₀ = Rate of force development at 50 milliseconds; RFD₁₀₀= Rate of force development at 100 milliseconds; RFD₁₅₀= Rate of force development at 150 milliseconds; RFD₂₀₀= rate of force development at 200 milliseconds; RFD₂₅₀= Rate of force development at 250 milliseconds; LLP= Lower limbs power output in counter movement jump. * = Significant correlation $p \leq 0.05$; (^p) = Pearson correlation; (^s)= Spearman correlation.

Table 2 highlights that the 1-RM load significantly and positively correlated with F_{max (iso)}, F_{max (dyn)}, P_{max}, and LLP. Figure 1 displays the average RFD values at the assessed intervals.

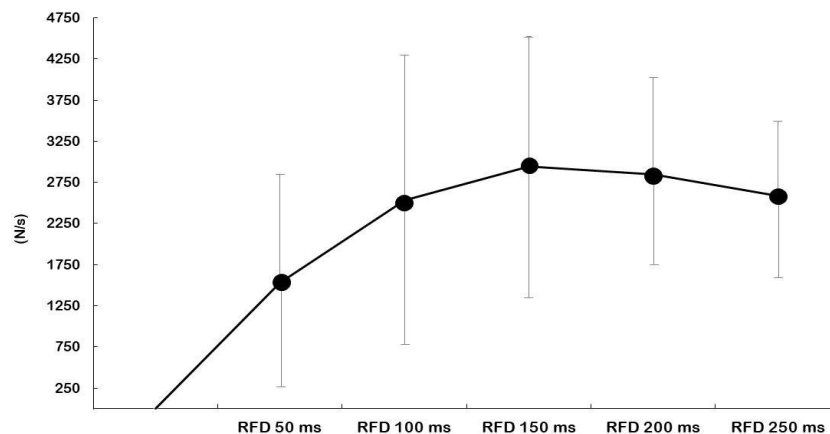


Figure 1: Mean of Rate of force Development in IMTP test intervals.

Discussion

This study aimed to evaluate the profile of strength and muscle power during maximal performance (1-RM test) in an OW exercise in CF practitioners. The main finding was that $F_{\max(\text{dyn})}$ and $P_{\max}$ were better associated with performance in the PC. $F_{\max(\text{dyn})}$ was classified as "very strong." The same classification also occurred between $P_{\max}$ and 1-RM. This was expected since these dynamic variables were evaluated directly during PC execution. Our findings corroborate those of (Martínez-Gómez et al., 2019), who found significant correlations between the indices of strength, muscle power and 1-RM in PC. In the case of the PC, it becomes more evident, as besides the fast movement, $P_{\max}$ is the product of $F_{\max(\text{dyn})}$ and lifting speed.

Although PC is a ballistic movement, $P_{\max}$ was not the variable that correlated most with 1-RM. An explanation for this would be that maximal power does not correspond to maximal load, but rather to an optimal load that can be lifted at the highest possible speed. This relationship between strength and speed is well defined in the literature, (Suchomel et al., 2020) and it means that to execute a movement at maximal power, the external load must be less than 1-RM (Poole et al., 2016). Thus, the relationship between maximal power and 1-RM is proportional until an optimal relationship between strength/speed. From this "optimal value," when increasing the load, power values decrease, due to lower movement speed (Toji & Kaneko, 2004). This nonlinear relationship is represented by a second-degree polynomial (a parabola). This reasoning is in agreement with the study carried out with the Hang PC, which identified that the external load had a significant influence on power, being maximized at a submaximal load, $\geq 70\%$ of 1-RM, showing a decrease in its value as the load increased. This nonlinear behavior of power was also identified in the back squat (Carroll et al., 2017).

$F_{\max(\text{iso})}$ showed significant correlations with 1-RM, being classified as "strong" and lower than the values of dynamic strength. This result is similar to that found by (De Witt et al., 2018) and occurs because isometric tests have a low correlation with dynamic activities (James et al., 2020). However, isometric strength can be beneficial to sports if performed in the fastest time in the form of ballistic isometric action. Unlike ramp isometric actions, where the force gradually builds up to its maximal without a focus on speed, ballistic isometric actions are more reflective of the quick movements often required in many sports. Despite this, this variable seems to influence the performance of sports modalities (Mcguigan et al., 2010), especially those that require power and RFD (Beckham et al., 2018). Compared to other populations where IMTP was applied, our results for $F_{\max(\text{iso})}$ were lower than in OW athletes (Stone et al., 2019). Although we did not specify the evaluation interval for RFD, we set a knee angle of 130 degrees during the IMTP. In our study, we kept the handle height the same for all participants. This means that, depending on a participant's height, the knee angle might vary from other studies, possibly affecting their ability to generate force, as pointed out by (Beckham et al., 2018). We found a stronger correlation between 1-RM and the dynamic variables when the muscles were active in the same way (concentrically).

The low correlation between all RFD values and 1-RM reinforces this reasoning. These correlation values were also reported by other studies (Tillin et al., 2010) (De Witt et al., 2018). It is suggested that the low correlation between RFD and 1-RM may be due to less influence of isometric tests and dynamic activity and as mentioned earlier, occurred because isometric tests do not correlate well with dynamic activities (James et al., 2020) due to differences in the length-tension relationship of the muscle in static postures when compared to a dynamic contraction. In this sense, several studies have identified that the correlation between dynamic strength and isometric performance depends on the similarity of joint angles (Kawamori et al., 2006). In the present study, the highest RFD value occurred at RFD_{150} (Figure 1). This differs from the results of OW athletes, where the highest RFD values occur around 250 ms (James et al., 2020). The highest RFD value at 150 ms could be explained by the types of training used in the WOD. Normally the training contains an AMRAP series where the highest number of repetitions possible is performed without the technique being compromised or for time (Maté-Muñoz et al., 2017). Repeating the action many times can lead to a decrease in the load that stimulates power, which in turn, could affect the RFD (James et al., 2020). The consequence of this training would lead to force production in a shorter time resulting in higher RFD values at 150 ms. As RFD has direct physiological/mechanical relevance for the performance of sports activities (Blazevich et al., 2020), RFD_{150} becomes an option for use in future studies in CF.

LLP showed a moderate correlation with 1-RM in the PC, corroborating with other studies (Carlock et al., 2004). According to (West et al., 2011), athletes with the greatest relative strength of the lower body would also have better performance in executing the CMJ. This occurs because, according to (Kawamori et al., 2006), the force and power produced by the lower limbs during a jump are crucial as they depend on maximizing force generation in these actions (Dos'Santos et al., 2017) (Thomas et al., 2015), thus being essential for the performance of PC. During dynamic activities, the stretch-shortening cycle helps store elastic energy which, in turn, improves the performance of the concentric phase of the movement (Fukutani et al., 2021). Although the lower limbs are crucial for generating force at the start of the PC, the stretch-shortening cycle is little used when compared to CMJ. Thus, we can understand the result of the correlation value found between LLP and 1-RM in the PC.

In this study, the highest correlation occurred between $F_{\max (dyn)}$ generated in the dynamic action and 1-RM in the PC. This indicates that by increasing strength through training, it would be possible to improve the 1-RM of this exercise. Thus, training to maximize strength becomes a priority for recreational CF practitioners. Similarly, $P_{\max}$ also showed an extraordinarily strong correlation. Training programs that prioritize increasing strength and power have the most potential to improve performance in this movement. It is up to the coaches to manage training programs and prioritize strength training in the initial phase of training, as well as the possibility of implementing power training. Moreover, in the current investigation, moderate correlations were found between $F_{\max (iso)}$ and 1-RM in the PC. This suggests that isometric strength could also be a way of monitoring performance in OW. The monitoring conducted through these tests has revealed varying capabilities in predicting loads associated with the 1-RM in OW movements. Ultimately, this analysis can serve to delineate the ideal load balancing between strength and speed concerning the external load (%1-RM) when the primary training goal is to enhance muscular power.

Limitations

We recognize some limitations within our study. Primarily, the majority of the CF practitioners examined were classified as recreational, potentially impacting the predictive performance variables due to their level of experience or familiarity. Consequently, it remains uncertain whether these variables would demonstrate associations with the performance of more seasoned practitioners. Furthermore, our results are based solely on a cross-sectional evaluation of the group, and it's crucial to acknowledge that their conditioning may undergo changes over time. Conducting further studies encompassing a broader range of OW exercises could offer more comprehensive insights into the relationship between strength variables and the execution of these movements.

Conclusions

We conclude that $F_{\max (dyn)}$ and $P_{\max}$ have a greater capacity to estimate 1-RM in the PC exercise in CF practitioners. LLP and $F_{\max (iso)}$ had a lower predictive capacity, certainly because they are not evaluated during PC movement. The RFD, despite being important, showed trivial-low predictive capacity, certainly because it was measured during the IMTP test. However, this variable is important to quantify the ability to generate rapid force. Further research is still needed to understand better how to control the load using field tests or specific tests in CF. This will allow for a better association between these variables and performance criteria, ultimately leading to more effective training strategies for practitioners.

Conflicts of interest - The authors declare no conflict of interest.

References:

- Banja, T., Assumpção, C. O., Pires, T., Cabido, C. E. T., Fermino, R. C., Andrade, R., Acioli, T., Cirilo-Sousa, M. D. S., Martins, F. J. A., Oliveira, S. F. M., & De Souza, T. M. F. (2023). Effect of lower limb fatigue and performance prediction in CrossFit®. *Journal of Physical Education and Sport*, 23(3), 714-721. <https://doi.org/10.7752/jpes.2023.03088>
- Beckham, G., Sato, K., Santana, H. A. P., Mizuguchi, S., Haff, G. G., & Stone, M. H. (2018). Effect of Body Position on Force Production During the Isometric Midthigh Pull. *Journal of Strength and Conditioning Research*, 32(1), 48-56. <https://doi.org/10.1519/JSC.0000000000001968>
- Blazevich, A. J., Wilson, C. J., Alcaraz, P. E., & Rubio-Arias, J. A. (2020). Effects of Resistance Training Movement Pattern and Velocity on Isometric Muscular Rate of Force Development: A Systematic Review with Meta-analysis and Meta-regression. *Sports Medicine*, 50(5), 943-963. <https://doi.org/10.1007/s40279-019-01239-x>
- Brady, C. J., Harrison, A. J., & Comyns, T. M. (2020). A review of the reliability of biomechanical variables produced during the isometric mid-thigh pull and isometric squat and the reporting of normative data. *Sports Biomechanics*, 19(1), 1-25. <https://doi.org/10.1080/14763141.2018.1452968>
- Carlock, J. M., Smith, S. L., Hartman, M. J., Morris, R. T., Ciroslan, D. A., Pierce, K. C., Newton, R. U., Harman, E. A., Sands, W. A., & Stone, M. H. (2004). The Relationship Between Vertical Jump Power Estimates and Weightlifting Ability: A Field-Test Approach. *The Journal of Strength and Conditioning Research*, 18(3), 534-539. <https://doi.org/10.1519/R-13213.1>
- Carreker, J. D., & Grosicki, G. J. (2020). Physiological Predictors of Performance on the CrossFit “Murph” Challenge. *Sports*, 8(7), 92. <https://doi.org/10.3390/sports8070092>
- Carroll, K., Sato, K., Bazyler, C., Triplett, N., & Stone, M. (2017). Increases in Variation of Barbell Kinematics Are Observed with Increasing Intensity in a Graded Back Squat Test. *Sports*, 5(3), 51. <https://doi.org/10.3390/sports5030051>
- De Witt, J. K., English, K. L., Crowell, J. B., Kalogera, K. L., Guilliams, M. E., Nieschwitz, B. E., Hanson, A. M., & Ploutz-Snyder, L. L. (2018). Isometric Midthigh Pull Reliability and Relationship to Deadlift One Repetition Maximum. *Journal of Strength and Conditioning Research*, 32(2), 528-533. <https://doi.org/10.1519/JSC.0000000000001605>

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- Dos'Santos, T., Thomas, C., Comfort, P., McMahon, J., & Jones, P. (2017). Relationships between Isometric Force-Time Characteristics and Dynamic Performance. *Sports*, 5(3), 68. <https://doi.org/10.3390/sports5030068>
- Feito, Y., Heinrich, K., Butcher, S., & Poston, W. (2018). High-Intensity Functional Training (HIFT): Definition and Research Implications for Improved Fitness. *Sports*, 6(3), 76. <https://doi.org/10.3390/sports6030076>
- Fukutani, A., Isaka, T., & Herzog, W. (2021). Evidence for Muscle Cell-Based Mechanisms of Enhanced Performance in Stretch-Shortening Cycle in Skeletal Muscle. *Frontiers in Physiology*, 11(January). <https://doi.org/10.3389/fphys.2020.609553>
- James, L. P., Suchomel, T. J., Comfort, P., Haff, G. G., & Connick, M. J. (2020). Rate of Force Development Adaptations After Weightlifting-Style Training. *Journal of Strength and Conditioning Research*, Publish Ah, 36(6), 1560-1567. <https://doi.org/10.1519/JSC.0000000000003673>
- Kawamori, N., Rossi, S. J., Justice, B. D., Haff, E. E., Pistilli, E. E., O'Bryant, H. S., Stone, M. H., & Haff, G. G. (2006). Peak Force and Rate of Force Development During Isometric and Dynamic Mid-Thigh Clean Pulls Performed at Various Intensities. *The Journal of Strength and Conditioning Research*, 20(3), 483-491. <https://doi.org/10.1519/18025.1>
- Lum, D., Haff, G. G., Barbosa, T. M., Tibana, R. A., de Farias, D. L., Nascimento, D. C., Da Silva-Grigoletto, M. E., Prestes, J., Torrejón, A., Balsalobre-Fernández, C., Haff, G. G., & García-Ramos, A. (2020). The Relationship between Isometric Force-Time Characteristics and Dynamic Performance: A Systematic Review. *Sports*, 18(3), 84-88. <https://doi.org/10.1016/j.ramd.2015.11.005>
- Mangine, G. T., Stratton, M. T., Almeda, C. G., Roberts, M. D., Esmat, T. A., VanDusseldorp, T. A., & Feito, Y. (2020). Physiological differences between advanced CrossFit athletes, recreational CrossFit participants, and physically-active adults. *PLoS ONE*, 15(4), 1-21. <https://doi.org/10.1371/journal.pone.0223548>
- Martínez-Gómez, R., Valenzuela, P. L., Barranco-Gil, D., Moral-González, S., García-González, A., & Lucia, A. (2019). Full-Squat as a Determinant of Performance in CrossFit. *International Journal of Sports Medicine*, 40(09), 592-596. <https://doi.org/10.1055/a-0960-9717>
- Maté-Muñoz, J. L., Lougedo, J. H., Barba, M., García-Fernández, P., Garnacho-Castaño, M. V., & Domínguez, R. (2017). Muscular fatigue in response to different modalities of CrossFit sessions. *PLoS ONE*, 12(7), 1-17. <https://doi.org/10.1371/journal.pone.0181855>
- Mcguigan, M., Newton, M., Winchester, J., & Nelson, A. (2010). Relationship Between Isometric and Dynamic Strength in Recreationally Trained Men. *Journal of Strength and Conditioning Research*, 24(9), 2570-2573. <https://doi.org/10.1519/JSC.0b013e3181ecd381>
- Meier, N., Schlie, J., & Schmidt, A. (2023). CrossFit®: 'Unknowable' or Predictable?—A Systematic Review on Predictors of CrossFit® Performance. *Sports*, 11(6), 112. <https://doi.org/10.3390/sports11060112>
- Moreira, V. M., Lima, L. C. R. de, Mortatti, A. L., Souza, T. M. F. de, Lima, F. V., Oliveira, S. F. M., Cabido, C. E. T., Aidar, F. J., Costa, M. da C., Pires, T., Acioli, T., Fermino, R. C., Assumpção, C. O., & Banja, T. (2023). Analysis of Muscle Strength and Electromyographic Activity during Different Deadlift Positions. *Muscles*, 2(2), 218-227. <https://doi.org/10.3390/muscles2020016>
- Peña, J., Moreno-Doutres, D., Peña, I., Chulvi-Medrano, I., Ortegón, A., Aguilera-Castells, J., & Buscà, B. (2021). Predicting the Unknown and the Unknowable. Are Anthropometric Measures and Fitness Profile Associated with the Outcome of a Simulated CrossFit® Competition? *International Journal of Environmental Research and Public Health*, 18(7), 3692. <https://doi.org/10.3390/ijerph18073692>
- Petrova, A., Bala, T., Masliak, I., & Mameshina, M. (2022). The effect of CrossFit exercises on the physical health level of 16–17-year-old boys. *Journal of Physical Education and Sport*, 22(4), 955-961. <https://doi.org/10.7752/jpes.2022.04121>
- Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical power: An important fatigue threshold in exercise physiology. *In Medicine and Science in Sports and Exercise*, 48(11) 2320-2334. <https://doi.org/10.1249/MSS.00000000000000939>
- Santos, P. D. G., Vaz, J. R., Correia, P. F., Valamatos, M. J., Veloso, A. P., & Pezarat-Correia, P. (2020). Muscle Synergies Reliability in the Power Clean Exercise. *Journal of Functional Morphology and Kinesiology*, 5(4), 75. <https://doi.org/10.3390/jfmk5040075>
- Stone, M., O'Bryant, H., Hornsby, G., Cunanan, A., Mizuguchi, S., Suarez, D. G., South, M., Marsh, D., Haff, G., Ramsey, M., Beckham, G., Santana, H., Wagle, J., Stone, M., & Pierce, K. (2019). Using the isometric mid- thigh pull in the monitoring of weightlifters : 25 + years of experience. *UKSCA Journal*, 54, 19-26.
- Suchomel, T. J., McKeever, S. M., McMahon, J. J., & Comfort, P. (2020). The Effect of Training with Weightlifting Catching or Pulling Derivatives on Squat Jump and Countermovement Jump Force-Time Adaptations. *Journal of Functional Morphology and Kinesiology*, 5(2), 28. <https://doi.org/10.3390/jfmk5020028>
- Thomas, C., Jones, P. A., Rothwell, J., Chiang, C. Y., & Comfort, P. (2015). An Investigation Into the Relationship Between Maximum Isometric Strength and Vertical Jump Performance. *Journal of Strength and Conditioning Research*, 29(8), 2176-2185. <https://doi.org/10.1519/JSC.0000000000000866>
-

- Tillin, N., Jimenez-Reyes, P., Pain, M., & Folland, J. (2010). Neuromuscular Performance of Explosive Power Athletes versus Untrained Individuals. *Medicine & Science in Sports & Exercise*, 42(4), 781-790. <https://doi.org/10.1249/MSS.0b013e3181be9c7e>
- Toji, H., & Kaneko, M. (2004). Effect of Multiple-Load Training on the Force-Velocity Relationship. *The Journal of Strength and Conditioning Research*, 18(4), 792-795. <https://doi.org/10.1519/13933.1>
- West, D. J., Owen, N. J., Jones, M. R., Bracken, R. M., Cook, C. J., Cunningham, D. J., Shearer, D. A., Finn, C. V., Newton, R. U., Crewther, B. T., & Kilduff, L. P. (2011). Relationships Between Force-Time Characteristics of the Isometric Midthigh Pull and Dynamic Performance in Professional Rugby League Players. *Journal of Strength and Conditioning Research*, 25(11), 3070-3075. <https://doi.org/10.1519/JSC.0b013e318212dcd5>