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Article

Predictive and Cross-Validation Analysis of Aerobic and Anaerobic Performance Based on Maximum Strength

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Abstract: To establish the capacity of absolute maximum strength and relative to body mass (BM) in deadlift (DL) and squat (SQ) exercises to estimate the maximum anaerobic running performance (MART) and maximum aerobic power (V_{Peak}), among individuals stratified into high (HS) vs. low strength score (LS). The sum of workloads (DL+SQ) was also analyzed and cross-validation was tested. Thirty-four students performed five visits in the first phase. In the first three visits the following were performed: sample characterization and consistency analysis of the maximum repetition (RM) for DL and SQ. Participants were stratified based on DL and SQ relativized by BM (DL/BM and SQ/BM). In the last two visits, MART and V_{Peak} were tested. Linear regression for HS participants did not predict MART for all strength measures. In contrast, the regressive model was significant for DL ($R^2 = 0.482$; $p = 0.002$), DL/BM ($R^2 = 0.764$; $p < 0.001$), SQ ($R^2 = 0.357$; $p = 0.011$) and SQ/BM ($R^2 = 0.644$; $p < 0.001$) in LS participants, compared to MART performance. For V_{Peak}, linear regression also did not demonstrate an association for all strength measures in HS participants. However, SQ ($R^2 = 0.309$; $p = 0.021$), DL/BM ($R^2 = 0.343$; $p = 0.013$) and SQ/BM ($R^2 = 0.618$; $p < 0.001$) were able to predict V_{Peak}. The prediction from the sum of the DL+SQ produced an association for MART ($R^2 = 0.451$; $p = 0.003$) and V_{Peak} ($R^2 = 0.273$; $p = 0.031$) in LS participants. In the second phase of the study, 17 participants performed cross-validation by testing the prediction equations. The same methodological procedures were performed for this phase, but only LS participants were tested. The Wilcoxon test compared real MART vs. predicted for DL ($p = 0.02$) and SQ ($p = 0.043$), showing differences, but not for DL/BM ($p = 0.051$) and SQ/BM ($p = 0.093$). The Wilcoxon test also showed differences for real V_{Peak} vs. predicted for DL/BM ($p = 0.002$), SQ ($p = 0.019$) and SQ/BM ($p = 0.05$). The MART predictive equation based on DL+SQ did not show differences ($p = 0.148$), but the same did not occur for V_{Peak} based on DL+SQ ($p = 0.008$). Maximum strength did not show predictive capacity in HS participants. However, it was significant for LS participants. DL showed greater predictive prominence for MART. In contrast, for V_{Peak}, SQ/BM satisfactorily explained the variations in running performance (61%). The

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predictive equations of MART by DL/BM and SQ/BM were shown to be accurate, as well as DL+SQ to predict MART.

Keywords: performance; strength training; VO_2Max; aerobic exercise

1. Introduction

Researchers and sports training professionals commonly seek to understand and optimize physical performance in athletes and recreational practitioners across different sports modalities [1–4]. There is an understanding that the ability to increase our physical and competitive performance, in general, is dependent on and better explained by its determining variables [5–7]. In the case of long-distance running, economy of movement, a variable expressed by the balance between submaximal oxygen consumption and the energy expended at a given stable velocity, appears to be the most relevant component for sporting success [8–11]. However, endurance or short-duration running also has a close relationship with the velocity indexes associated with the occurrence of VO_2Max [7], anaerobic energy pathways [12] and strength production capacity [13–19].

Strength training has been shown to be an effective strategy for improving running performance [20], and its effects seem better associated with neural adaptations than actual structural elements [9–11,14]. Previous studies had already established the relationship between absolute maximum strength or strength relative to body mass with running performance, reinforcing the perspective of positive interference of muscular strength on aerobic performance, suggesting that the greater the external load-lifting capacity, the shorter the running time would be; however, sprinting skills were mainly analyzed [14–19,21]. Determining how much maximum strength interferes with and explains variations in running performance, whether aerobic or anaerobic, although not a new subject, remains inconclusive, especially for endurance performance. Furthermore, we do not know whether the development of maximum strength would produce the same associations across different levels of physical capacity, which leads us to explore the topic from a new perspective.

Movement professionals understand that strength is therefore a relevant element to include in a training program [20,22]. Despite that, defining which exercise patterns would best associate with running performance still requires research. Historically, exercises with kinematic patterns involving simultaneous hip, knee and ankle extension, such as the squat (SQ) and its derivatives, with different manifestations of strength, are used as a predictive mechanism for running performance [13,15,16,18,19,21,23], explained mainly under movement mechanics analogous to running.

On the other hand, based on the descriptive rationale of the movement and the specificity, other kinematically similar exercises, such as the deadlift (DL) movement, could demonstrate viability as a predictive strategy [24]. Although they are kinematically similar movements, particularities were observed when their kinetics were documented by Choe et al. [25]. The authors demonstrate that the DL exercise presents a higher peak joint torque on the hip extensors compared to the squat (3.59 vs. 2.98 $Nm \cdot kg^{-1}$, $d = 0.81$, $p < 0.001$), while the SQ exercise presents a higher peak joint moment on the knees (2.14 vs. 1.18 $Nm \cdot kg^{-1}$, $d = 1.44$ $p < 0.001$) [25].

Despite this understanding, no study to date has established the associative capacity of DL to explain running performance, with only jumping performance being investigated [24], which requires analysis. Furthermore, understanding that both movements produce particular kinetics, but that they are commonly required in the running pattern, we speculate that the sum of the absolute external loads between DL and SQ could complement each other and better explain aerobic and anaerobic running performance; however, this perspective still requires investigation. Furthermore, to our knowledge, there are no studies that have developed and validated equations to estimate aerobic and anaerobic performance based on absolute and relative maximum strength.

Therefore, the primary objective of this study was to establish the relationship between maximum force production, represented by the maximum amount of external load lifted (kg), and normalized by body mass ($BM^{1.0}$) in DL and SQ exercises in order to analyze whether the anaerobic performance of a maximal anaerobic running test (MART) and maximum progressive aerobic power (V_{Peak}) could be satisfactorily estimated through strength for individuals stratified into high strength scores and low strength scores. Secondarily, we will analyze whether the sum of absolute loads (DL+SQ workload) would present a better predictive value for aerobic and anaerobic performance than individual loads, both for individuals with high strength scores and for those with low strength scores. Thus, we developed and investigated the validity of prediction equations for aerobic and anaerobic performance based on absolute and relative maximum strength. Finally, we will establish the reliability of maximum strength (RM) measurements.

Our hypothesis (H^1) is that the regressive model will present significant predictive outcomes for individuals with high and low strength scores, both for DL and SQ movements analyzed by absolute loads and for loads allometrically relativized by $BM^{1.0}$. In addition, we believe that the sum of DL and SQ loads can produce better coefficients of determination than individual DL and SQ loads to estimate anaerobic and aerobic performance in laboratory tests (H^2). Finally, 1RM determinations will present excellent correlation coefficients (H^3).

Subsequently, a second stage of data collection aimed to perform cross-validation of the generated equations. We believe that the equations will present a significant association between the real and predicted measurements ($H^{1'}$).

2. Materials and Methods

2.1. Experimental Approach

This study was conducted based on the STROBE Statement guidelines for cross-sectional studies (https://www.strobe-statement.org/checklists—accessed on 1 August 2024) [26] and was divided into two distinct collections. The study followed Resolution 466/2012 of the National Health Council and was approved by the Research Ethics Committee (number—3.858.767—CAAE: 26916819.9.0000.5512). All participants were recruited by convenience, in a public call at a private university in midwest Brazil, and signed a consent form containing pertinent information about the experimental procedures, as well as the possible risks and discomforts involved in the study. This information was also explained verbally in detail. After selection, acceptance and understanding of the risks inherent to physical exercise, all participants signed the consent form.

The first collection was a cross-sectional observational study and was established in a non-randomized and controlled manner. As a primary outcome measure, we analyzed the associative potential of the absolute strength of the DL and SQ exercises on the performance of maximal aerobic power and anaerobic power, as well as whether the allometric normalizations of the external loads relativized by body mass could better predict performance (H^1). As a secondary outcome (H^2), we focused on analyzing whether the sum of the absolute loads would be better associated with aerobic and anaerobic performance than the individual loads. Finally, we established the reliability of the strength measures (H^3).

A second cross-sectional observational characteristic collection was carried out, and the cross-validation of the equations produced was analyzed.

2.2. Study Design

2.2.1. First Data Collection (For the Development of the Equation)

Participants signed an informed consent form and came to the laboratory for a total of five visits. The first visit consisted of a characterization of the sample based on anthropometric procedures, as well as a maximum repetition (RM) test of the DL and SQ movements and familiarization with the MART. On the second visit, participants performed the RM of DL or SQ, applied in random order. On the third visit, a new RM of DL or SQ was performed, establishing the consistency of the measurement. The fourth visit consisted of the execution of the MART. Finally, on the last visit, the maximum progressive aerobic performance protocol was performed. During all visits, participants were encouraged to perform to the best of their ability. All procedures were performed at the same time of day and at a controlled temperature between 21 and 23°.

2.2.2. Second Data Collection (To Test the Validity of the Equation)

Participants signed an informed consent form and attended only four visits. The first visit consisted of determining the sample characteristics based on anthropometric procedures and an RM test of the DL and SQ movements (randomized). On the second visit, a new RM test of one of the movements was performed, as well as familiarization with the MART. On the third and fourth visits, a maximum MART and the maximum progressive aerobic performance protocol were performed in random order. For all tests, there was encouragement to achieve maximum performance. All procedures were carried out at the same time of day and at a controlled temperature between 21 and 23°.

2.3. Sample

In the first collection, 34 university students, 12 of whom were women, recreationally trained for running, at low risk according to the risk stratification criteria proposed by the ACSM and apparently healthy, were invited to participate in the present study after a public call at a university in central-west Brazil. The call took place during the period from August 2022 to January 2023.

In the second collection, 32 university students, 10 of whom were women, recreationally trained and apparently healthy, were invited to participate in the study via a public call at a university in central-west Brazil. The second call took place during the period from January 2024 to May 2024.

For both collections, participants were included based on the levels of force relativized by body mass in the DL and SQ movements (between 1.0 and 2.5 kg/kg) and on recreational running performances for a distance of 5 KM (up to 30 min). However, for the second collection, only participants with less than 1.5 of external load ratio relativized by body mass in the movements in question were included [27].

As exclusion criteria, participants who used substances that alter the cardiovascular system or substances that artificially promote improved strength, as well as those with recurrent previous injuries, were excluded. Participants who obtained strength levels lower than 1.0, considering the relationship between load and body mass, were considered beginners and were also eliminated from the study [27]. This care was taken because we wanted to investigate whether muscular strength could affect running performance and, in beginners, with little or no experience in strength training, this aspect could mask the results. Therefore, we excluded them from the analysis a priori, avoiding any biased analysis a posteriori. All participants had the procedures agreed upon in advance and their doubts clarified.

The sample size was defined based on the following parameters for linear regression: random model, considering the following attributes: tails = 2; H1 = 0.4; alpha error = 0.05;

power = 0.95; number of predictors = 2, resulting in a total sample of 34 participants. Therefore, 32 subjects resulted in a priori statistical power > 0.86, which is the minimum accepted for studies of a biological nature [28].

2.4. Procedures

2.4.1. Morphological and Anthropometric Procedures

Standard measurements established by the International Society for the Advancement of Kinanthropometry (ISAK) were used, consisting of the following indicators: body mass and height (WELMY 110 CH, Brazil), as well as skinfold. The relative body fat was estimated using the skinfold technique, in which body density is calculated using the seven-fold protocol proposed by Jackson and Pollock [29,30] where values are collected at each point in a rotational sequence on the right side of the body and the average value of three measures is recorded. The measurements were performed by a single investigator using a skinfold compass (Slim Guide, Rosscraft, Canada). After calculating the body density, it was converted to a percentage of body fat using the equation proposed by Siri [31].

2.4.2. One-Repetition Maximum Test

To perform the 1RM test, the participant was required to perform one repetition with the greatest possible load in the DL and SQ exercises. To do this, there was a progression and three attempts with a five-minute interval between them. For the deadlift movement, the participants started with their arms aligned at shoulder width, feet at shoulder width and a pronated grip. The bar started from the floor with the knees and hips flexed, and the torso flexed forward. In the concentric phase, the bar is raised from the floor to the waist line. Attempts in which the participant was unable to establish the extended alignment position were not considered.

For the squat movement, each participant underwent a load progression and three attempts with a five-minute interval between them to determine 1RM. Participants started with the bar on their backs, performing the eccentric phase of the movement during the downward movement to the lowest angles of the knee and hip. The concentric phase consisted of raising the bar to the starting point in full extension. Attempts in which the participants were unable to establish the alignment position in maximum extension were not considered.

Before the three attempts, participants performed a load progression as follows: (a) standard warm-up with only the barbell weight (12 to 15 reps); (b) one set of six to eight reps with 50% of the maximum load estimated by the volunteer (3 min interval); (c) one set of three reps with 75% of the maximum load estimated (5 min interval). After the progression, the actual 1RM attempts began. Strong verbal encouragement was provided for all strength measurements.

2.4.3. Anaerobic Performance Test (MART)

A three-minute warm-up was performed at 5.0 km·h^{-1} and without inclination. After the warm-up phase, progressive stimuli of 20 s and passive recovery of 100 s were performed, starting at 10.2 km·h^{-1} with increments of 1.0 km·h^{-1} at each stage with a fixed inclination of 12% until maximum voluntary exhaustion, adapted from the protocol of Rusko and Nummela et al. [32]. The velocity corresponding to the last stage of the test was considered as the MART velocity (vMART). In cases of an incomplete attempt, the previous stage counted as the actual vMART [5,32,33].

2.4.4. Progressive Maximal Effort Performance Test

The treadmill test was conducted in a laboratory environment with an initial velocity of 8 km·h^{-1} for 2 min. After the start, a load progression of 1 km·h^{-1} every 2 min was performed until the maximum effort was reached. VO_2Max was estimated from the maximum velocity (V_{Peak}) reached during the progressive maximal test and estimated from the metabolic equation for running proposed by the American College of Sports Medicine (ACSM). Equation (1) presents the predictive equation for determining VO_{2Max}.

$$VO_{2Max} = [0.2 \times \text{velocity (m/min)} + 0.9 \times \text{velocity (m/min)} \times \text{slope (centesimal)}] \quad (1)$$

2.4.5. Allometry

The standard exponent was used for the body mass (BM) variable, scaling the relative strength to 1.0 ($kg/BM^{1.0}$). Predictive analyses were performed based on all scenarios, normalized and non-normalized.

2.4.6. Stratification of Training Levels

To stratify participants between predictive strategy groups, values greater than 1.8 for the DL exercise and 1.5 for the SQ exercise were considered, as suggested by Santos Junior et al. [27] for advanced participants. This group was called the "high strength score" group. The "low strength score" group was defined based on strength levels relativized by body mass between 1.0 and 1.6 for the DL exercise and 1.0 and 1.4 for SQ.

2.4.7. Data Analysis and Processing

To avoid possible biases in the analysis, the data were collected by two different researchers associated with the project and the research group (P.A. and P.D.). A third evaluator was responsible for the data analysis. The researcher responsible for the data analysis remained blinded throughout the data collection process (group leader A.S.).

2.5. Statistical Analysis

The normality of the data was tested by the Shapiro–Wilk test. Since the variables did not violate normality, the data were expressed as mean and standard deviation. Furthermore, a Student *t*-test for independents samples was used to determine the differences between the baseline measures for sample characterization and predictive variables. A linear regression was applied to investigate the level of association between aerobic and anaerobic performance and the different maximal strength strata (high vs. low strength score), as well as to produce a predictor equation for aerobic and anaerobic performance from the different maximal strength strata (high vs. low strength score). It is suggested to adopt linear regression first if the response function is unknown [34]. In addition, an analysis of variance (ANOVA for quadratic model regression) was applied to verify whether the adjustment of the regression model as a predictor of aerobic and anaerobic powers was significant. Finally, an intraclass correlation coefficient (ICC) was used to determine the reliability of the strength measurement.

For the second collection, after analyzing data normality, Spearman's correlation was used to determine the level of association between the actual performance measures and the predicted ones. The Wilcoxon test was used to subsequently compare the actual and predicted values (cross-validation). A significance level of $p < 0.05$ was assumed and the SPSS statistical package version 20 was used (IBM Corp., Armonk, NY, USA).

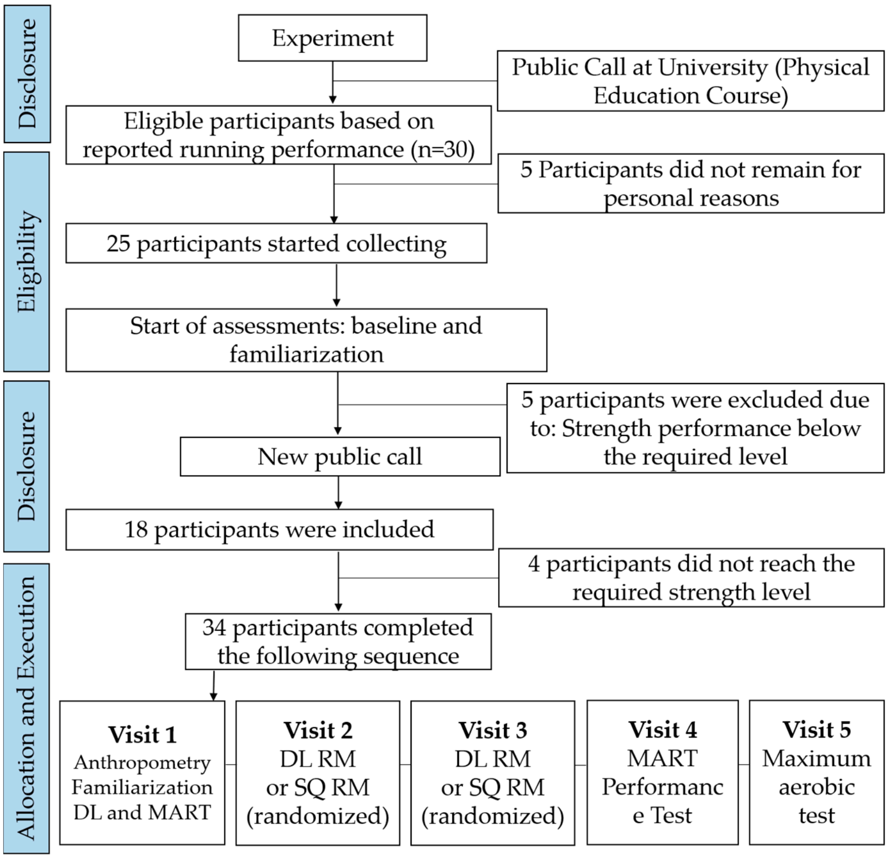
3. Results (First Collection)

The sample characterization data were stratified by high training score and low training score groups and are expressed as mean and standard deviation (SD) and presented in Table 1. The sample normality was duly tested by the Shapiro–Wilk test, presenting a normal distribution pattern for all dependent variables ($p < 0.05$). Flowchart 1 presents the results of the recruitment, entry, eligibility and exclusion of the participants in the experimental collection. The Student *t*-test for independent groups designed to determine the differences in characterization between groups showed equality in the variables of age ($p = 0.575$), BM ($p = 0.673$), height ($p = 0.523$) and BMI ($p = 0.981$).

Table 1. Characterization of the sample stratified by training level.

	High Strength Score				**Low Strength Score**			
	Age (Years)	**BM (kg)**	**Height (m)**	**BMI ($kg{\cdot}m^{-2}$)**	**Age (Years)**	**BM (kg)**	**Height (m)**	**BMI ($kg{\cdot}m^{-2}$)**
Mean	28.0	73.9	1.71	25.1	26.6	75.6	1.75	24.5
SD	8.1	11.4	0.08	2.7	6.3	11.9	0.09	3.2

SD = standard deviation; BMI = body mass index; BM = body mass.



Flowchart 1. Flowchart of inclusion and exclusion of study participants.

The independent Student *t*-test compared participants with high vs. low strength scores, indicating differences between groups for maximum DL strength ($p < 0.0001$), relative DL/BM strength ($p < 0.0001$), maximum SQ strength ($p < 0.0001$) and relative SQ/BM strength ($p < 0.0001$). The baseline variables are presented in Table 2.

The performance results of vMART and the maximum incremental test, as well as the estimated metabolic demand values for both, are presented in Table 3. There were no differences for any baseline dependent variables related to the running tests (V_{Peak}: $p = 0.228$; vMART: $p = 0.145$).

Table 2. Stratification by strength level in DL and SQ movements, relativized or not by BM.

	High Strength Score				Low Strength Score			
	DL	**DL/BM**	**SQ**	**SQ/BM**	**DL**	**DL/BM**	**SQ**	**SQ/BM**
	(kg)	**(kg/kg)**	**(kg)**	**(kg/kg)**	**(kg)**	**(kg/kg)**	**(kg)**	**(kg/kg)**
Mean	145.3	2.0	111.1	1.5	105.4 *	1.4 *	86.3 *	1.1 *
SD	21.6	0.1	16.4	0.3	27.9	0.3	22.7	0.2

SD = standard deviation; DL = deadlift; SQ = squat; DL/BM = deadlift load relative to body mass; SQ/BM = squat load relative to body mass; * significant differences between the group with the lowest strength score and the highest strength score.

Table 3. Results of strength and maximum progressive aerobic tests.

	High Strength Score				Low Strength Score			
	VO_2Max	**V_{Peak}**	**VO_2**	**MART**	**VO_2Max**	**V_{Peak}**	**VO_2**	**vMART**
	$mL \cdot kg^{-1} \cdot min^{-1}$	**$km \cdot h^{-1}$**	**$mL \cdot kg^{-1} \cdot min^{-1}$**	**$km \cdot h^{-1}$**	**$mL \cdot kg^{-1} \cdot min^{-1}$**	**$km \cdot h^{-1}$**	**$mL \cdot kg^{-1} \cdot min^{-1}$**	**$km \cdot h^{-1}$**
Mean	53.3	14.9	95.9	18.0	50.8	14.2	90.5	16.9
SD	5.5	1.6	8.3	1.6	6.6	2.0	12.5	2.4

SD = standard deviation; V_{Peak} = achieved velocity at the last stage of the maximum incremental test; vMART = achieved velocity at the end of the MART; VO_2Max = metabolic demand was estimated based on the ACSM equations; VO_2 = metabolic demand determined based on the peak velocity achieved in the MART with 12% incline.

3.1. Primary Outcomes

For linear regression analysis, the prerequisites of linearity between the predicted and predictor variables, as well as homoscedasticity and normality of distribution of residuals, were accepted. The regression model for participants with high strength scores did not predict vMART performance for either the DL (r = 0.193; R^2 = 0.037; F(1,15) = 0.581; $p = 0.458$) or DL/BM (r = 0.057; R^2 = 0.003; F(1,15) = 0.048; $p = 0.829$) exercise or the SQ (r = 0.106; R^2 = 0.011; F(1,15) = 0.170; $p = 0.686$) or SQ/BM (r = 0.076; R^2 = 0.006; F(1,15) = 0.087; $p = 0.772$) exercise. Thus, the DL RM test does not explain the variations in vMART performance, suggesting that strength from a certain level does not influence anaerobic running performance.

Conversely, linear regression demonstrated a positive result for predicting vMART performance in the face of lower strength scores. The regression model presented significant results for DL (r = 0.694; R^2 = 0.482; F(1,15) = 13.95; p = 0.002), DL/BM (r = 0.874; R^2 = 0.764; F(1,15) = 48.493; $p < 0.001$) and SQ (r = 0.597; R^2 = 0.357; F(1,15) = 8.328; $p = 0.011$) and SQ/BM (r = 0.803; R^2 = 0.644; F(1,15) = 27.154; $p < 0.001$). Figure 1A,B present the regression plots for vMART performance for DL movement and Figure 2A,B present the regression analyses between vMART and SQ.

Regarding aerobic power analysis, the linear regression also did not demonstrate a significant association between the movements of DL (r = 0.158; R^2 = 0.025; F(1,15) = 0.384; $p = 0.545$), DL/BM (r = 0.265; R^2 = 0.070; F(1,15) = 1.123; $p = 0.306$), SQ (r = 0.123; R^2 = 0.018; F(1,15) = 0.267; $p = 0.613$), SQ/BM (r = 0.102; R^2 = 0.010; F(1,15) = 0.157; $p = 0.698$) and V_{Peak} for participants with high training scores.

The regressive model using DL movement (r = 0.467; R^2 = 0.218; F(1,15) = 4.192; $p = 0.059$) to predict V_{Peak} did not show statistical significance. In contrast, SQ was able to predict V_{Peak} performance (r = 0.555; R^2 = 0.309; F(1,15) = 6.692; $p = 0.021$). When we used allometric relativization, the model was also positive for DL/BM (r = 0.586; R^2 = 0.343; F(1,15) = 7.841; $p = 0.013$) predicting V_{Peak} performance. Finally, the regression of V_{Peak} by the predictor variable SQ/BM was positive, presenting significant results between the measured and predictor variables (r = 0.786; R^2 = 0.618; F(1,15) = 24.264;

$p < 0.001$). Figure 3A,B show the regression graphs for the V_{Peak} performance for both investigated movements.

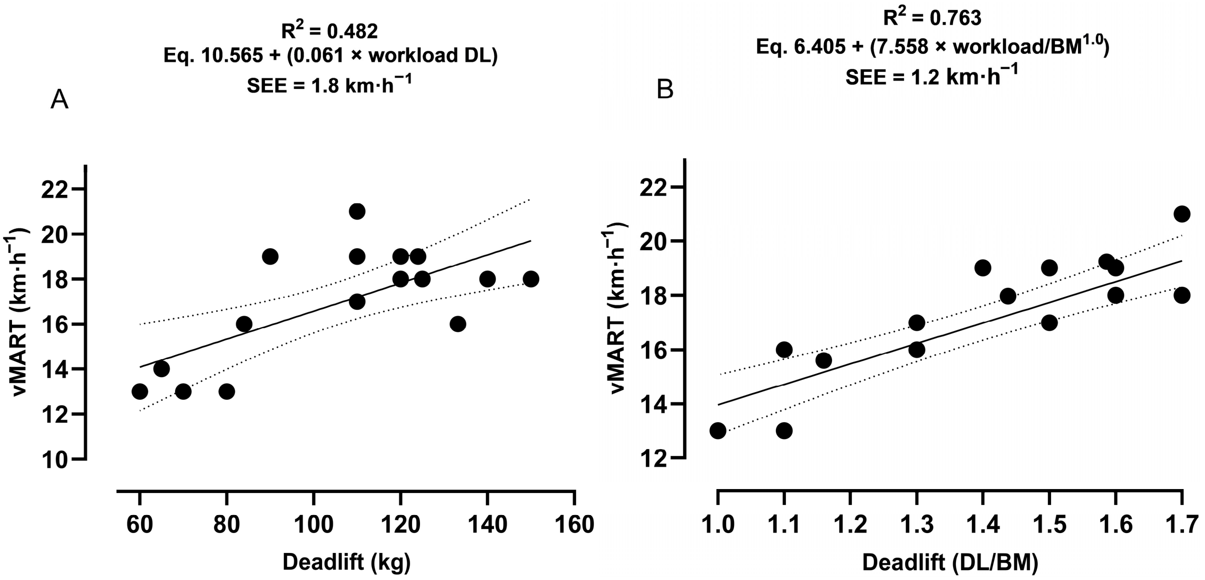


Figure 1. Representation of the equation of the linear regression of the variables absolute DL (**A**) and relative DL by body mass (**B**). R^2 = coefficient of determination; DL/BM = external deadlift workload relativized by body mass; vMART = peak velocity obtained in the incremental MART; SEE = standard error of the estimate.

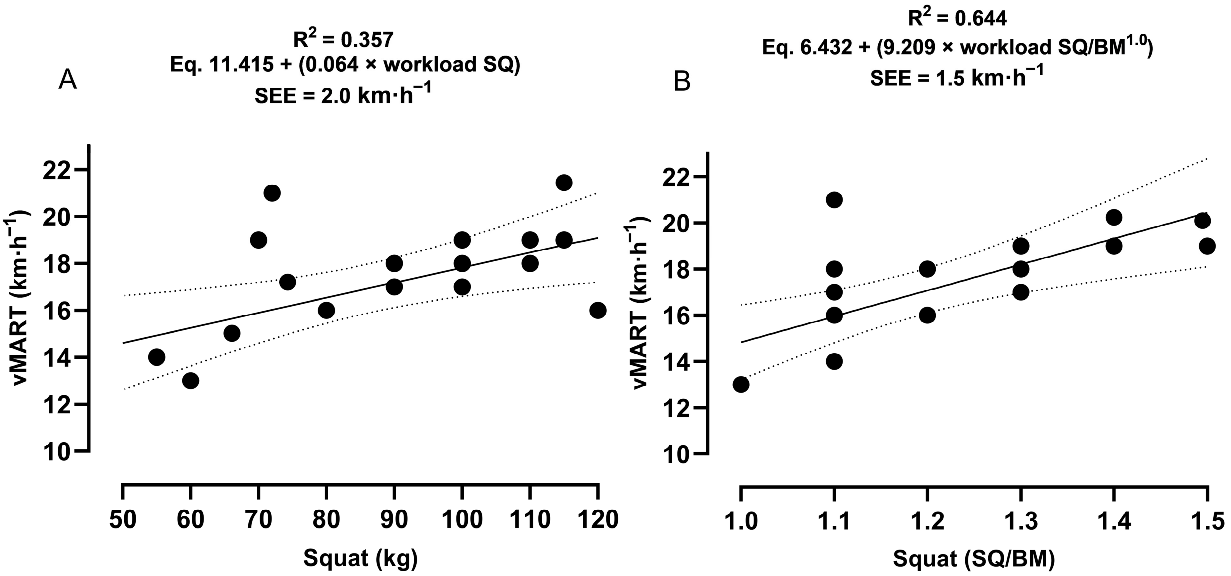


Figure 2. Representation of the equation of the linear regression of the variables absolute SQ (**A**) and relative SQ by body mass (**B**). R^2 = coefficient of determination; DL/BM = external deadlift workload relativized by body mass; SQ/BM = external squat workload relativized by body mass; vMART = peak velocity obtained in the incremental MART; SEE = standard error of the estimate.

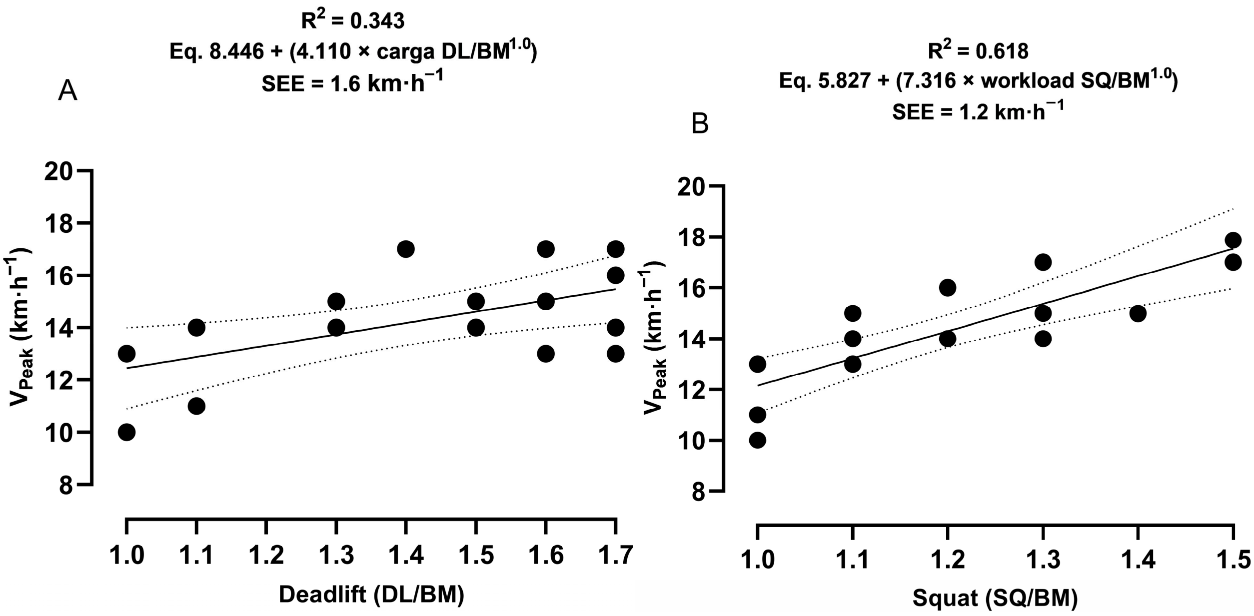


Figure 3. Representation of the linear regression equation of the variables DL (**A**) and SQ (**B**) relativized by body mass. R^2 = coefficient of determination; DL/BM = deadlift external workload relativized by body mass; SQ/BM = squat external workload relativized by body mass; V_{Peak} = peak velocity obtained in the maximum incremental test; SEE = standard error of the estimate.

3.2. Secondary Outcome

The sum of the external loads was calculated and used to predict performance. There were significant differences between the scores of high vs. low level of training ($p < 0.0001$). Table 4 presents the sums of the DL and SQ workloads.

Table 4. Sum of workloads between DL and SQ movements.

	High Strength Score	Low Strength Score
	(kg)	(kg)
Mean	256.5	191.7 *
SD	33.5	49.1

SD = standard deviation; * significant differences between groups.

The predictive model using the sum of loads in both movements was tested based on the assumptions of linearity and normality. The sum of loads (DL+SQ) did not produce a significant association with MART performance (r = 0.176; R^2 = 0.031; F(1,15) = 0.481; $p = 0.499$) for participants with a high training score. When analyzing participants with a lower training score, the linear regression, although significant, does not appear to be superior to other isolated predictive models (r = 0.671; R^2 = 0.451; F(1,15) = 12.318; $p = 0.003$).

The predictive model using the sum of workloads as a predictor variable of V_{Peak} did not present significant results when considering the high levels of training scores (r = 0.037; R^2 = 0.001; F(1,15) = 0.021; $p = 0.888$) but was significant when considering the lowest levels of training (r = 0.523; R^2 = 0.273; F(1,15) = 5.646; $p = 0.031$). Figure 4A,B show the regression graphs for the sum of performances.

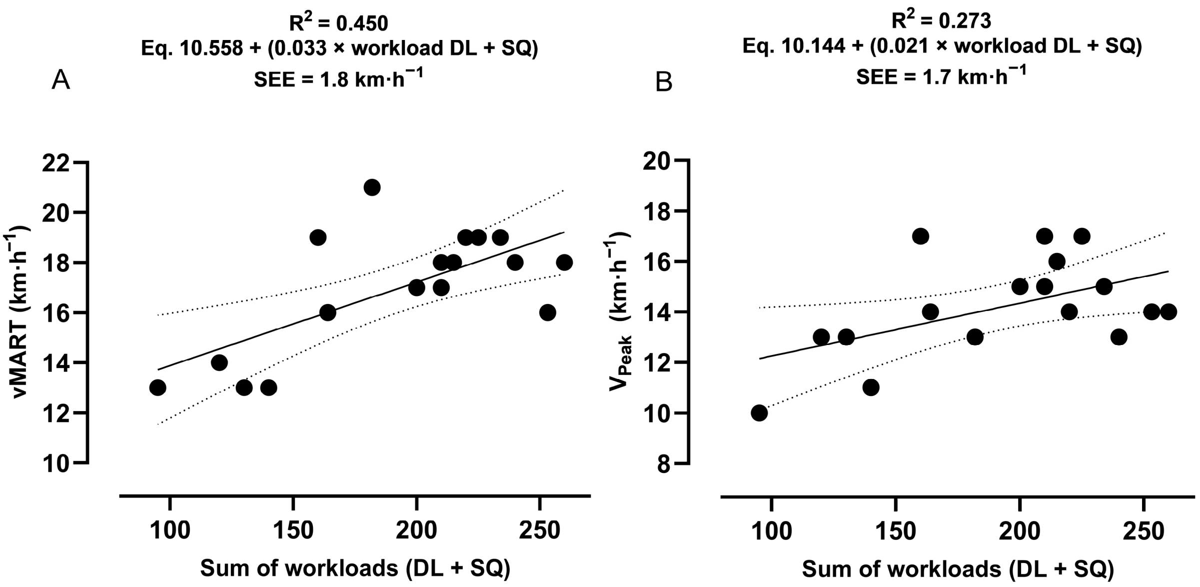


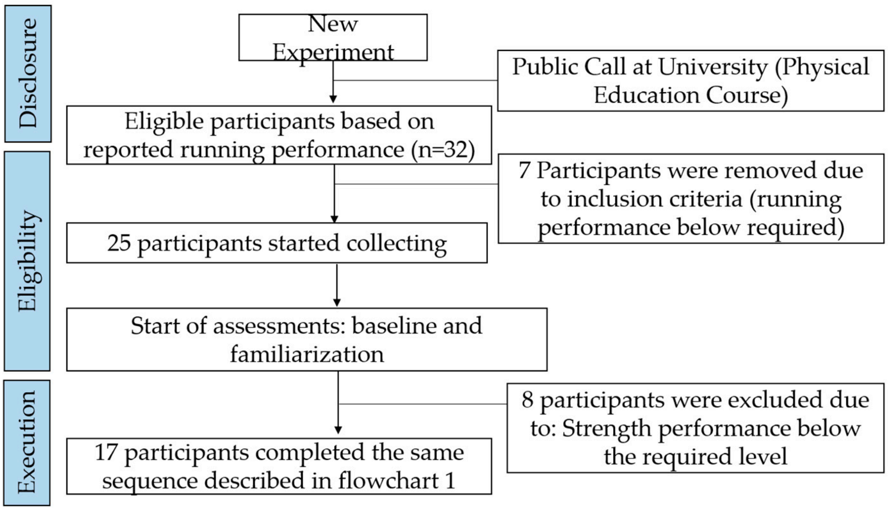
Figure 4. Representation of the linear regression equation of the sum of the DL and SQ workloads for vMART (**A**) and V_{Peak} (**B**), respectively. R^2 = coefficient of determination; vMART = peak velocity obtained in the incremental MART; V_{Peak} = peak velocity obtained in the maximum incremental test; SEE = standard error of the estimate.

3.3. Tertiary Outcome

Finally, the reliability of the strength measurements was initially examined in only the first 22 participants (G power = correlation biserial model; two tails; effect size = 0.7; alpha = 0.01; power = 0.95). The ICC analysis indicated excellent stability of the measurement (ICC = 0.99) between the sessions performed for the DL movement (117.2 ± 32.7 kg–120.2 ± 34.4 kg, respectively, for session 1 × 2). For the SQ movement, the ICC showed an association of 0.99 (91.4 ± 24.6 kg–93.2 ± 22.3 kg, respectively, for session 1 × 2).

4. Cross-Validation Results (Second Collection)

Flowchart 2 presents the results of the recruitment, entry, eligibility and exclusion of participants from the experimental collection.



Flowchart 2. Flowchart of inclusion and exclusion of study participants.

After analyzing statistical assumptions, the data distribution violated normality assumptions for the measurement variable vMART predicted by absolute and relative DL

($p = 0.007$; $p = 0.009$, respectively) or absolute and relative SQ ($p = 0.017$; $p = 0.003$, respectively), as well as for the measurement variable V_{Peak} predicted by relative DL ($p = 0.092$) and V_{Peak} predicted by absolute and relative SQ ($p = 0.020$; $p = 0.004$). The same occurred for the sum of the workloads for prediction of vMART ($p = 0.050$) and sum of the loads for prediction of V_{Peak} ($p = 0.046$). Therefore, non-parametric statistical tests were used.

Table 5 presents the characterization of the new sample participating in the validation process of the prediction equations. Table 6 presents the strength and running performance data. Table 7 presents the results of the association between the real performance measures vMART and V_{Peak} vs. the different results predicted by absolute and relative values of DL and SQ, as well as the sum of the workloads.

Table 5. Sample characterization of participants (n = 17; 10 Women and 7 Men).

	Age	**BM**	**Fat**	**DL/BM**	**SQ/BM**
	(Years)	**(kg)**	**(%)**	**(kg/kg)**	**(kg/kg)**
Mean	26.0	68.4	18.6	1.3	1.1
SD	5.7	14.3	12.3	0.2	0.1

SD = standard deviation; BM = body mass; BMI = body mass; Fat = percentage fat; DL/BM = deadlift relative to body mass; SQ/BM = squat relative to body mass.

Table 6. Performance measures of the new sample with low strength score.

	DL	**SQ**	**vMART**	$\mathbf{V_{Peak}}$
	(kg)	**(kg)**	**(km·h^{-1})**	**(km·h^{-1})**
Mean	90.6	74.4	15.3	12.6
SD	29.5	17.1	1.9	1.5

SD = standard deviation; DL = deadlift; SQ = squat; V_{Peak} = peak of velocity in the maximum incremental test.

Table 7. Association between the real performance measures vMART and V_{Peak} with the prediction equations by DL and SQ, as well as the sum of the workloads.

	Eq. Prediction DL		**Eq. Prediction SQ**		**Sum**
	(Abs)	**(Rel)**	**(Abs)**	**(Rel)**	**(DL+SQ)**
vMART Real	r = 0.766; $p = 0.001$ *	r = 0.757; $p = 0.001$ *	r = 0.545; $p = 0.024$ *	r = 0.125; $p = 0.634$	r = 0.683; $p = 0.003$ *
V_{Peak} Real		r = 0.651; $p = 0.005$ *	r = 0.430; $p = 0.085$	r = 0.089; $p = 0.733$	r = 0.573; $p = 0.016$ *

DL = deadlift; SQ = squat; vMART Real = peak of velocity obtained in the MART test; V_{Peak} Real = peak of velocity obtained in the maximum incremental test; Eq. = prediction equation; Abs = absolute values; Rel = values relativized by body mass. * = significant association.

The Wilcoxon test for the measures of real vMART vs. vMART predicted by DL ($p = 0.02$) and SQ ($p = 0.043$) showed significant differences, but not for DL/BM ($p = 0.051$) and SQ/BM ($p = 0.093$). The same statistical treatment was used for the measures of real V_{Peak} vs. V_{Peak} predicted by DL/BM ($p = 0.002$), SQ ($p = 0.019$) and SQ/BM ($p = 0.05$), demonstrating significant differences between the real measure and that predicted by the equation. For the prediction of vMART performance from the sum of the DL and SQ workloads, the comparison by the Wilcoxon test did not demonstrate significant differences ($p = 0.148$), however, the same did not occur for the prediction of V_{Peak} performance from the sum of the DL and SQ workloads ($p = 0.008$), where significant differences were observed. Table 8 presents the typical measurement error for the real vs. predicted variables. Figures 5 and 6 present the comparisons between the real vs. predicted measurements by the equation, using DL, SQ and the sum of the workloads. The Bland–Altman agreement analysis can be seen in the supplementary material (Figures S1 and S2).

Table 8. Typical measurement error for real and predicted performance variables.

	vMART				
	DL	**DL/BM**	**SQ**	**SQ/BM**	**DL+SQ**
			(km·h^{-1})		
TME (Abs)	0.87	0.95	1.54	2.70	0.98
TME (Rel)	5.5%	6.0%	9.9%	17.3%	6.3%
	V_{Peak}				
	DL	DL/BM	SQ (km·h^{-1})	SQ/BM	DL+SQ
TME (Abs)		2.67	1.30	2.26	0.89
TME (Rel)		18.7%	10.0%	17.4%	6.9%

TME = typical measurement error; DL = measure of absolute strength of deadlift; DL/BM = measure of strength relativized by body mass; SQ = measure of absolute strength of squat; SQ/BM = measure of strength relativized by body mass; DL+SQ = sum of deadlift and squat workloads.

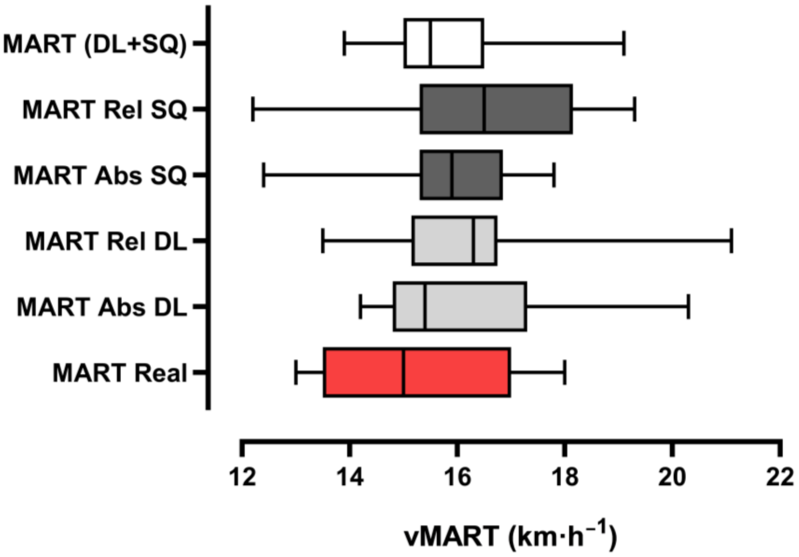


Figure 5. Box-and-whisker plot of real and predicted vMART performances, absolute and relative DL and SQ, as well as the sum of the workloads (DL+SQ).

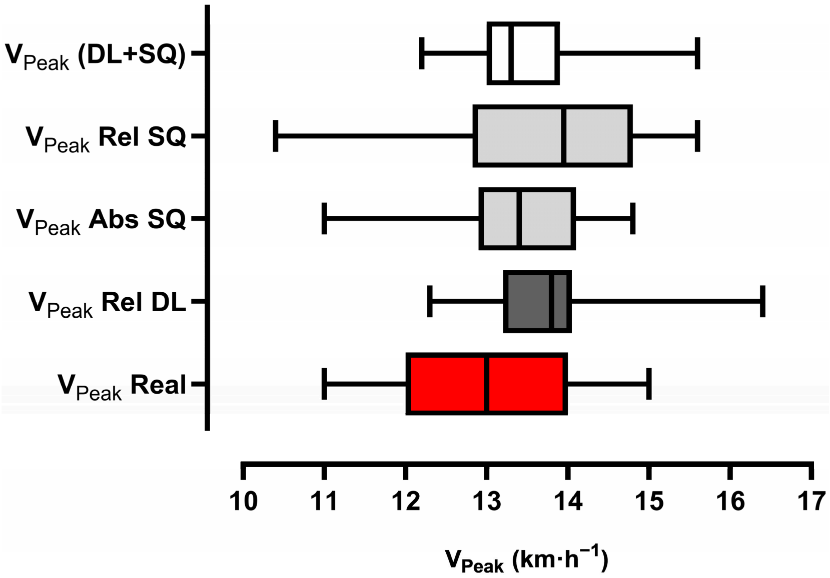


Figure 6. Box-and-whisker plot of real and predicted V_{Peak} performances, absolute and relative DL and SQ, as well as the sum of the workloads (DL+SQ).

5. Discussion

The primary objective of this study was to establish the relationship between the production of absolute maximum strength, represented by the maximum amount of external load lifted (kg), and relativized by $BM^{1.0}$ in the DL and SQ exercises in order to analyze whether the anaerobic performance of the MART and maximum aerobic performance V_{Peak} could be satisfactorily estimated through strength. Our primary hypothesis was partially accepted, since the strength levels did not significantly impact the anaerobic and aerobic performance in individuals with a large maximum strength base, suggesting the existence of a ceiling at which the maximum strength levels would continue to interfere in the improvement of performance. In contrast, we observed in individuals with lower strength scores that the increase in maximum strength would be appropriate as a strategy to influence running performance. In this sense, our study appears to be the first to present the perspective of a limit in which strength is really important, and that after such a limit, there is no longer a need to invest in new attempts at increments.

The importance of strength training for the development of running performance is reasonably understood in the literature [8–10,13]. When combined with running, it appears to reflect significant adaptations, which in turn would positively influence running economy and muscular power factors [11]. Sentija, Marsic and Dizdar [14] demonstrate that strength training in physically active young individuals can induce increases in both anaerobic and aerobic endurance. In untrained individuals, there is also a small influence on maximum oxygen consumption. Logically, our study was not a chronic intervention based on the exercises presented; however, such an argumentative reference of improvement reinforces the plausibility of the investigation, so the effects of the components related to maximum strength are in fact related to running performance [15,16,18,21].

Furthermore, to the best of our knowledge, our study appears to be the first in demonstrating that the DL movement can be an important predictor of both anaerobic and aerobic performance. The DL movement is similar to the SQ regarding its mechanical description (planes and axes of movement). It is an extension of the hip, knee and ankle, however, with different initial positioning, main action required (concentric only) and amplitude. Choe et al. [25] also demonstrate that DL presents a greater peak joint torque on the hip extensors compared to SQ (3.59 vs. 2.98 $Nm \cdot kg^{-1}$, $d = 0.81$, $p < 0.001$). In this sense, we know that, mainly, the requirement for large ranges of motion when running is reasonably small, which makes the SQ an apparently unspecific element. Additionally, the extension movements of the hip, knee and ankle joints are the main accelerators of BM when performing short-term movements, such as in the MART [15,16]. Therefore, based mainly on the premise of specificity, there seems to be plausibility in using DL exercise in the context of running performance, and our study corroborates this argument, especially when the external load is relativized by BM (DL vs. MART $-$ $R^2 = 0.482$; DL/BM vs. vMART $-$ $R^2 = 0.763$; DL/BM vs. V_{Peak} $-$ $R^2 = 0.343$). Therefore, the DL movement relativized by BM presents itself as a great alternative, explaining 76% of the variations in anaerobic and aerobic performance in participants with lower strength score levels (<1.5 of BM).

However, despite this approach, in our study we saw that SQ is also relevant to explaining running performance, even when faced with a kinematic pattern that is different from that used in running (deep squat). Since the movement of SQ, as well as its variations in the face of different manifestations of strength, appears in the literature as an optional evaluation measure and predictive mechanism [16–19], our results are in line with this, presenting a coefficient of determination capable of explaining 35% of the variations in anaerobic performance when we consider the gross external load ($R^2 = 0.357$), increasing its associative capacity to 64% when relativized by $BM^{1.0}$ ($R^2 = 0.644$). The prediction of

V_{Peak}, however, only presented associative potential when relativized by $BM^{1.0}$ (SQ/BM vs. $V_{Peak} - R^2 = 0.614$), explaining 61% of the variations in aerobic performance.

Furthermore, apparently, in a way that we are unaware of having been performed before, we based our secondary hypothesis on the perspective that the combination of external loads in the DL and SQ movements could better predict both performances compared to the measurement of strength alone. This justification originated from the idea that both movements produce specific (higher) torque on a given joint, as suggested by Choe et al. [25]. However, our hypothesis H^2 was refuted, because despite the viability of its use as a performance predictor mechanism, the sum of strength measurements did not show superiority in the predictive model of anaerobic ($R^2 = 0.45$) and aerobic ($R^2 = 0.27$) performance compared to the strength models alone, therefore perhaps making it unnecessary to use two distinct assessments.

Comparison with the literature proved to be complex given its unique condition, since we do not have similar studies that carried out the force summation strategy. However, it is possible to make inferences about prediction analyses in different modalities, such as in CrossFit. Previous studies analyzed the sum of maximum strength variables in DL, "clean" (snatch) and "press" movements (any overhead pushing movements) and observed that the sum of the variables produced better predictive responses than the exercises alone, distancing themselves from our results [35]. The authors also observed a negative correlation between VO_2Max ($r = -0.79$; $p = 0.001$), the maximum load lifted in the clean movement ($r = -0.86$; $p = 0.001$), squat ($r = -0.65$; $p = 0.008$) and front squat ($r = -0.79$; $p = 0.002$) and the sum of the absolute workloads ($r = -0.78$; $p = 0.001$) with performance in the Open 15.5 workout [36]. Additionally, Meier, Rabel and Schmidt [37,38] are aligned with these statements, highlighting that the sum of the strengths of their personal records (PRs) in the main basic movements can be used as a measure of success to predict physical performance.

Our hypothesis H^3 only reinforces the perspective observed on the subject in the literature. Reliability analysis has been extensively discussed for years, and we already know that although it varies from study to study, or from movement to movement, Grgic, Lazinica, Schoenfeld and Pedisic [39] admit in their systematic review that, in view of 32 studies on the test–retest reliability of the 1RM assessment ($n = 1595$), they observed that 92% of the studies with moderate to excellent methodological quality presented ICC ≥ 0.90. In our study, the results were not different from the literature, presenting excellent stability for the DL movement (CCI = 0.99; 117.2 ± 32.7 kg vs. 120.2 ± 34.4 kg), as well as for the SQ movement (CCI = 0.99; 91.4 ± 24.6 kg vs. 93.2 ± 22.3 kg).

Finally, the second part of our study aimed to perform cross-validation of the generated equations. We believed that the equations would show a significant association between the actual and predicted measures (H^1). However, our hypothesis was partially accepted. The predictive equations using DL and DL/BM showed a strong association between the actual and predicted MART performance measures ($r = 0.766$ and $r = 0.757 - p = 0.001$, respectively), with an estimated measurement error of 5.5 and 6.0%, respectively. Despite this small measurement error, only the equation generated by DL/BM did not differ significantly when compared ($p = 0.051$). Similarly, DL/BM also showed a moderate relationship between the actual and predicted V_{Peak} measurements ($r = 0.651$; $p = 0.005$), however, with a very high measurement error (18.7%) and statistically different from the actual V_{Peak} measurement ($p = 0.002$), which makes it unusable. When observing the SQ and SQ/BM measurements in the predictive context of the MART, the estimated SQ was different from the real measurement ($p = 0.019$), however, SQ/BM showed borderline statistical equality between the predicted and the real measurement ($p = 0.05$), despite the high measurement error of 17.3%. The same did not occur for SQ and SQ/BM as a predictive mechanism for V_{Peak}. In this case, the correlation did not demonstrate a significant relationship (r = 0.430 − p = 0.085; r = 0.089 − p = 0.733), in addition to presenting significant statistical differences, therefore, its practical use is not appropriate.

Ultimately, we observed a good relationship between predicted and predictor measures for the sum of SQ and DL workload (r = 0.683 − p = 0.003; r = 0.573 − p = 0.016, respectively, for actual MART and V_{Peak} measures), however, only anaerobic performance benefited from the prediction, showing no differences between predicted and actual measures (p = 0.148), as well as a low aggregate measurement error (6.3%). Despite these outcomes, as previously mentioned, it seems unnecessary to use both loads, since the measurement of DL or DL/BM to predict MART results alone already presents good correlation and low measurement error. We know that the cross-validation process is a procedure required to analyze whether a measure actually predicts what it is intended to predict [40]. Evidence over the past few years has produced predictive equations for maximal oxygen consumption [41,42] as well as for external load variables related to aerobic and anaerobic performance [43–45], with varying results. Mahar et al. [43] analyzed the predictive validity of the equations generated by the Progressive Aerobic Cardiovascular Endurance Run (PACER) test in adolescents and observed that the regression demonstrated that the quadratic model and the linear model were slightly more accurate than other VO_2Max estimation models. The correlations for these models between measured and estimated VO_2Max were r = 0.75 and r = 0.74 and had very similar levels of precision (total error of 6.37 and 6.59 $mL \cdot kg^{-1} \cdot min^{-1}$, respectively). Similar to our outcomes, for some predictive models, despite presenting moderate to high correlations, low estimation accuracies were observed (V_{Peak} estimation through DL/BM = 18.7%; SQ = 10.0%; SQ/BM = 17.4% typical measurement error).

Finally, the fact that the sample was selected by convenience, in this case, recreationally active university students, can be considered a limitation of the present study, as it may limit the extrapolation of these findings to other populations. Therefore, we suggest that the results of the present study be interpreted with some caution.

6. Conclusions

Maximum strength levels did not show a significant relationship between aerobic and anaerobic performance for individuals with high strength levels. However, for participants with lower strength scores, the associations between maximum and relative strength of DL and SQ were significant. The strength for both DL and SQ exercises relative to BM showed higher coefficients of determination compared to the predictive model by absolute external load. It is worth noting that the DL movement had greater predictive prominence for the anaerobic MART, explaining 76% of the variations in running performance. In contrast, for aerobic performance, SQ movement relative to BM explained the variations in running performance better.

Despite the apparent feasibility of using the sum of DL and SQ workloads as a predictor of running performance, these were not superior to the individual predictive model. The ICC analysis indicated excellent stability of the measurement (ICC = 0.99) between the sessions performed for the DL movement.

Finally, cross-validation showed significant accuracy of DL/BM to estimate MART performance, but the same did not occur for V_{Peak} estimates, presenting significant divergences.

In practical terms, if coaches, physiologists and running enthusiasts wish to promote an improvement in running performance, both aerobic and anaerobic, we suggest introducing the deadlift and squat exercises into their training programs, but with light loads. Regarding the use of strength loads to predict running performance, we suggest using models normalized by body mass, which presented higher coefficients of determination.

Specifically for anaerobic running, the deadlift exercise proved to be more robust, while for aerobic running, the squat exercise appears to be a better predictor. This is unique knowledge and can be applied to runners whose goal is to improve, evaluate and monitor performance. We suggest that future research investigate the associations tested in the present study in different populations and, therefore, develop new equations to predict running performance, based on strength variables.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15020693/s1, Figure S1: Bland-Altman concordance analysis for vMART performance, real vs. predicted; Figure S2: Bland-Altman concordance analysis for VPeak performance, real vs. predicted.

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