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ORIGINAL ARTICLE

Peak versus Mean Propulsive Power Outputs: Which Variable is More Related to Jump Squat Performance?

Short title: Muscle power and jump-squat performance

Irineu Loturco[1,2*], Lucas A. Pereira[1], Ronaldo Kobal[1], Katia Kitamura[1], Cesar C. Cal Abad[1], Fábio Y. Nakamura[1,3], Chi Nan Pai[2]

1 - NAR - Nucleus of High Performance in Sport, São Paulo, SP, Brazil

2 - Department of Mechatronics Engineering, University of São Paulo, SP, Brazil

3 - Department of Physical Education, State University of Londrina, PR, Brazil

Conflicts of interest. The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

*Corresponding author:

E-mail: irineu.loturco@terra.com.br (IL)

ABSTRACT

Background: This study aimed to compare the predictive value of muscle power (peak power, mean power until the peak-velocity or mean propulsive power) in relation to the jump height achieved during the jump squat performed at different loads.

Methods: One hundred and ninety-four elite athletes performed jump squats against loads corresponding to 40%, 60%, and 80% of their respective body-mass. A linear regression analysis was performed to establish the relationship between muscle power expressions and jump squat height.

Results: The coefficient of determination (R^2) in the different linear regression models between muscle power-related variables and jump squat height, for the different load ranges, varied from 0.50 to 0.57 (for absolute power values) and from 0.72 to 0.78 (for relative power values [W/kg]). The mean propulsive power presented similar capacity to predict the jump squat height as the peak power-related values. For all analysed variables, this prediction power was increased when the absolute power values were normalized by the individuals' body-mass.

Conclusion: Selection of the values related to the mean propulsive phase to assess top-level athletes might be considered as an advantageous alternative, due to its adequacy to properly reflect the neuromuscular potential of the subjects in both ballistic and traditional exercises.

Keywords: optimal loads - muscle power - elite athletes - jump height - peak velocity.

Introduction

Muscle power is one of the most investigated physical capacities in the field of sport science.[1] Conceptually, this interest is based on its close relationships with actual sports performance[2-5] and its extensive use as a parameter of intensity to prescribe and implement effective neuromuscular training strategies.[6, 7] In recent years, there have been several studies showing that training at optimum power zones (i.e., using loads capable of maximizing muscle power outputs) may produce positive adaptations at both ends of the force-velocity curve (i.e., high-force/low-velocity and low-force/high-velocity portions), in both recreationally and highly-trained subjects.[1, 6-8]

Despite its wide utilization as a neuromechanical reference in exercise science,[6-8] the selection of the most suitable measure to define and describe muscle power is somewhat complex.[9-11] In this sense, some authors[1, 9-12] have highlighted that the range of loads able to maximize mechanical muscle power might be significantly affected by the individual training status, type of movement involved, and method used to find this variable. As an attempt to clarify this issue, Sanchez-Medina et al.[13] reported that the use of the mean mechanical values related to the propulsive phase of the movement (rather than to the entire concentric portion of the lifting) could better indicate neuromechanical differences between two given individuals. The reason for this assumption is that, when compared with mean power and peak power (PP), the mean propulsive power (MPP) outputs have been shown to be more stable and accurate markers of optimum power loads.[13] Together, these points provide a strong argument for the preferential use of propulsive outcomes during neuromuscular assessments performed in top-level athletes.

From a mechanical perspective, the propulsive phase can be defined as the concentric portion of the lift where the acceleration (a) is greater than the (opposite) acceleration due to gravity (g).[13, 14] As a consequence, in this specific segment of the movement the force applied by the athlete is positive ($F > 0$). Nevertheless, in the final stages of the concentric phase, there is a portion where the deceleration rate is superior to that estimated based exclusively on the gravity effect. This occurs because the subject must exert a force in a direction contrary to the lifting, in order to stop the movement.[13, 15] Notably, throughout this braking phase, the resultant force is negative ($F < 0$), since $a < g$.[13] Undoubtedly, this mechanical phenomenon has crucial implications for training and testing purposes.

In theory, the braking phase occurs during any given strength-power exercise, except when the movements are performed under ballistic conditions (e.g., loaded jumps). Indeed, these movements circumvent any deceleration phase, by requiring athletes to accelerate (as rapidly as possible) throughout the complete range of motion toward the takeoff.[1, 16] For some authors, this absence of deceleration during the concentric action could partially compromise the use of the propulsive values in ballistic exercises.[17] In this regard, Garcia-Ramos et al.[17] revealed a very slight difference in favor of peak velocity (i.e., the maximum instantaneous velocity attained during the concentric phase) when comparing the predictive power of this variable (in relation to jump squat height [JSH]) with the predictive power of the final propulsive velocity (i.e., the bar-velocity just before the acceleration of the bar was lower than $-9.81\ m \cdot s^{-2}$) ($R^2 = 0.931$ vs 0.913, respectively).

Actually, from a statistical point of view, according to their very strong power of prediction (> 90%), both variables (peak and final propulsive velocity) can be used to estimate the height reached by a given subject during a jump squat execution with high precision.[18] Although it is recognized that the height achieved during a vertical jump is determined by the net-velocity achieved immediately before the take-off,[9, 19, 20] it seems that the end of the propulsive phase (which occurs on average 30 ms after the beginning of the flight-phase) is not able to disturb the close relationship that exists between the dependent (JSH) and independent (final propulsive velocity) variables. In fact, the validity of the mechanical values related to the propulsive phase of ballistics may be confirmed through analysis of the strong correlations found between jump squat MPP and actual sports performance.[2, 3] Furthermore, training at the optimum power zone (using loads that maximize the MPP in jump squat exercise) is capable of producing significant improvements in strength, power and speed capacities of top-level athletes and recreationally trained subjects.[1, 6, 8]

To date, there is no consensus about the best muscle power measure to use to assess and train elite athletes. This is still more problematic when coaches and sport scientists are analyzing the values collected in both traditional and ballistic exercises at the same time (i.e., half squats and jump squats). Arguably, using the same power output expression would allow consistent comparisons between mechanics and power zones for training prescription of these exercises.[21] Therefore, it is relevant to determine whether PP and MPP values obtained during ballistic exercises (e.g., jump squat) present similar abilities to predict performance (i.e., jump height). Accordingly, the aim of this study was to compare the predictive value of dynamic measures (PP, mean power until the peak velocity [MPUP] and MPP) in relation to the jump height reached during jump squat exercises performed at different percentages of loads, across different groups of top-level athletes.

Materials and Methods

Study Design

All elite athletes involved in this study were assessed during the competitive phase of the season, after being previously familiarized with the investigated exercise (jump squat), equipment (Smith machine, encoder and contact platform), and testing facilities. The subjects were required to refrain from any heavy workout for 2 days prior to the testing day, to remain in a fasted state for 2 h and not to consume caffeine or alcohol for 24 h prior to the tests. As the jump height was the performance outcome, athletes were encouraged to jump as high as possible in all attempts. The variables analysed in this study were: JSH – the height recorded by the contact platform when performing the jump squats; MPUP and mean force until peak velocity (MFUP) – mean power and force value measured from the beginning of the concentric phase until the instant that the maximal velocity was registered, respectively; MPP and mean propulsive force (MPF) – mean power and force value that refer to the upward portion of the jump squat during which bar-acceleration is greater than acceleration due to gravity, respectively; and PP and peak force (PF) – maximum power and force value registered during the concentric phase, respectively. Prior to the beginning of the tests, the athletes performed a standardized 15-minute warm-up including general (i.e., running at a moderate self-selected pace for 5 minutes followed by 5 minutes of lower limb active but smooth stretching) and specific exercises (i.e., plyometrics and jump squats using light-loads for 5 minutes) and 5 minutes of active rest before commencing the test.

Participants

One hundred and ninety-four elite athletes from fourteen sports disciplines (assigned to eleven groups) volunteered to participate in this study: combat sports athletes (karate and taekwondo; men: n = 19; 22.6 ± 2.3 years; 175.2 ± 6.3 cm; 68.2 ± 14.3 kg);

endurance runners (men: n = 13; 25.6 ± 4.2 years; 170.3 ± 3.0 cm; 58.9 ± 8.5 kg); futsal players (men: n = 26; 23.5 ± 3.3 years; 176.3 ± 5.7 cm; 70.8 ± 7.5 kg); judo athletes (men: n = 10; 25.2 ± 3.1 years; 180.2 ± 10.3 cm; 84.4 ± 10.0 kg; women: n = 10; 23.2 ± 4.2 years; 169.3 ± 8.2 cm; 63.4 ± 10.0 kg); rugby sevens players (men: n = 17; 25.3 ± 3.1 years; 179.2 ± 7.5 cm; 81.1 ± 9.5 kg); strikers (muay-thai and boxing athletes; men: n = 22; 23.7 ± 2.8 years; 178.4 ± 5.1 cm; 74.1 ± 11.4 kg); tennis players (men: n = 10; 23.6 ± 4.9 years; 181.3 ± 5.4 cm; 76.9 ± 8.2 kg); power track & field athletes ([P T&F] sprinters, jumpers, decathletes and heptathletes; men: n = 42; 26.2 ± 5.1 years; 178.8 ± 5.2 cm; 76.6 ± 6.9 kg; women: n = 18; 24.5 ± 4.2 years; 167.3 ± 6.2 cm; 58.2 ± 5.8 kg); and volleyball players (men: n = 8; 29.2 ± 4.5 years; 195.7 ± 11.2 cm; 93.8 ± 11.1 kg). The sample comprised athletes involved in national and international competitions, including members of Brazilian national teams, Olympic, Pan American and National medallists, and World Champions, thus attesting their very high level of competitiveness. Participants were briefed about the experimental risks and benefits of research participation, and signed an informed consent form agreeing to take part in the sample. The study was approved by the Bandeirante-Anhanguera University Ethics Committee (registration number 949.022).

Assessment of force and power related variables and jump squat height at loads corresponding to 40%, 60% and 80% of the athletes' body mass

Force and power related variables, and JSH were assessed in the jump squat exercise, performed on a Smith machine (adapted by Hammer Strength, Rosemont, IL, USA). The elite athletes were instructed to execute sets of 3 repetitions at maximal velocity at each load starting at 40% of the athletes' body mass; afterwards the load was increased to 60 and 80% of body mass. Subjects executed a knee flexion until the thigh was parallel to the ground and, after an initial command, jumped as fast as possible. Prior to each muscle power assessment, an experienced test administrator instructed the participant to maintain constant downward pressure on the barbell throughout the jump, to prevent the bar moving independently of the body.[12, 22] A 5-minute interval was provided between sets. To calculate the variables, a linear velocity transducer (T-Force, Dynamic Measurement System; Ergotech Consulting S.L., Murcia, Spain) was attached to the bar on the Smith machine. The displacement was obtained by integration of v data with respect to time, which presents an accuracy of ± 0.5 mm; the instantaneous acceleration (a) was obtained from differentiation of v with respect to time; the bar velocity and acceleration, presenting an associated error of < 0.25%; instantaneous force (F) was calculated as $F = m \cdot (a + g)$, where m is the moving mass (kg) and g is the acceleration due to gravity.[13, 23, 24] Instantaneous bar velocity was sampled at a frequency of 1000 Hz. The resolution of the A/D card is 14 bits. The proprietary software used is commercial and was provided by the manufacturer in conjunction with the equipment. The JSH was determined using a contact platform (Smart Jump; Fusion Sport, Coopers Plains, Australia), being estimated by the flight time, according to the standard procedures reported by Bosco et al.[25] We considered the best JSH at each load for data analysis purposes. To avoid misinterpretation of the force and power outputs and taking into consideration the influence of body mass on the calculation and, consequently, on the bar-velocity and JSH, we normalized these values by dividing the absolute force and power value by the athletes' body mass. Test-retest reliability for jump squat outputs as measured by the coefficient of variation was < 5%.

Statistical analysis

Normality was checked via the Shapiro Wilk test. The means and standard deviation (SD) were used to represent centrality and spread of data. A one-way ANOVA with Hochberg's GT2 post-hoc analysis was used to compare the force and power related variables, and JSH among the eleven groups of athletes. A linear regression analysis was performed to analyse the capacity of the power related variables (MPUP, MPP, and PP) to predict the JSH. Squared residuals analyses were used as proxies for the goodness of fit. The comparison of the squared residuals from the linear regression models among the different power related variables was performed by means of the one-way ANOVA to determine whether the variance of the squared residuals for one interpretation was significantly different from the variance of the other interpretation. If so, the best fit was represented by the parameters which resulted in the smallest variance of squared residuals. Finally, the correlations between force-related variables (MFUP, MPF, and PF) and JSH were checked using the Pearson's product moment test. The threshold used to qualitatively assess the correlations was based on the following criteria: <0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9, very large; >0.9 nearly perfect.[26] The statistical significance level for all tests was set at $P< 0.05$.

Results

All analysed data presented normal distribution. Table I displays the comparisons of the JSH and power-related variables among the groups pertaining to the different sports disciplines. The power-related variables measured across the different loads showed a consistent pattern: The P T&F male athletes presented significantly higher values ($P< 0.05$) than the other groups of athletes, excepting the male judo athletes and rugby sevens players.

*****INSERT TABLE I HERE*****

Table II shows the comparisons of the power-related variables relative to athletes' body mass among the investigated athletic groups. P T&F male athletes demonstrated significantly higher values for all power-related variables at the different loads in comparison to the other groups of athletes ($P < 0.05$). The rugby sevens players presented higher values of power variables at the different loads than the endurance runners, tennis players, and volleyball players ($P < 0.05$).

*****INSERT TABLE II HERE*****

Table III demonstrates the comparison of the force-related variables among the different athletic groups, during the execution of jump squats. The force-related variables presented some specific group differences, which followed similar trends to those observed in the power-related variables.

*****INSERT TABLE III HERE*****

Table IV displays the comparisons of the force-related variables relative to athletes' body mass among the different sports disciplines. P T&F male athletes demonstrated significantly higher values for all force variables at the different loads in comparison to the other groups ($P < 0.05$), excepting the judo male athletes and rugby sevens players. Rugby sevens players presented higher values of force variables at the different loads than the endurance runners and volleyball players ($P < 0.05$).

*****INSERT TABLE IV HERE*****

Figure 1 depicts the linear regression between the power-related variables and respective JSH at the load corresponding to 40% of athletes' body mass. The coefficient of determination in the different linear regression models varied between 0.50 and 0.53 for absolute power measures, and between 0.72 and 0.74 for relative power measures.

*****INSERT FIGURE 1 HERE*****

Figure 2 demonstrates the linear regression between the power-related variables and the respective JSH at the load corresponding to 60% of athletes' body mass. The coefficient of determination in the different linear regression models varied between 0.54 and 0.55 for absolute power measures, and between 0.73 and 0.78 for relative power measures.

*****INSERT FIGURE 2 HERE*****

Figure 3 shows the linear regression between the power-related variables and the respective JH at the load corresponding to 80% of athletes' body mass. The coefficient of determination in the different linear regression models varied between 0.55 and 0.56 for absolute power measures, and between 0.77 and 0.78 for relative power measures.

*****INSERT FIGURE 3 HERE*****

In table V the correlations between the force-related variables and respective JSH are shown at the loads corresponding to 40%, 60%, and 80% of the athletes' body mass. Small (r = 0.48) to large (r = 0.76) significant (P< 0.01) correlations were observed. Finally, table VI demonstrates the comparison of the squared residuals from the linear regression between the power-related variables and the respective JSH at the loads corresponding to 40%, 60%, and 80% of the athletes' body mass. No differences in the squared residuals were found among the different power-related variables (P> 0.05).

*****INSERT TABLE V HERE*****

*****INSERT TABLE VI HERE*****

Discussion

This is the first study to simultaneously compare the ability of three different muscle power measurements to precisely predict the JSH. The main result reported here is that, independent of the mechanical parameter used to express their respective outputs, all three relative muscle power measures (i.e., PP, MPUP and MPP) were equally capable of estimating with a good power of prediction ($R^2 \approx 0.75$) the height reached by a top-level athlete during a jump squat execution at three different loading conditions (using 40, 60, and 80% of his/her respective body mass).

Observing the results above, it is possible to note that all three measures (PP, MPPPV, and MPP) are strongly related to JSH and this is independent of the loading intensity (i.e., light- or heavy-loads). As previously stated, it is important to emphasize that the vertical jump height (in loaded or unloaded conditions) is determined by the peak of velocity, which inevitably occurs immediately before the takeoff.[9, 19, 20] Hence, from a mechanical standpoint, it is predictable that dynamic measurements calculated from the peak velocity (PP and MPPPV) may be closely related to the height reached by elite athletes during jump squats. Similarly, since the propulsive phase ends just ≈ 30 ms after the takeoff and the velocity at this point is only ≈ 3% lower than the peak velocity *(data from the current results)*, it is also rational to expect that the MPP (which is calculated from the mean propulsive velocity) might also work as a precise predictor of JSH. From our data, considering the similar prediction power of the relative outputs of PP, MPP, and MPUPV ($R^2 \approx 0.75$; in relation to the JSH), it is possible to assert that these three measures can be equally used to assess ballistic exercises, for both training and testing purposes.

Although these close relationships seem to be independent of the loading intensity, it is worth mentioning that there is an expressive increase in the prediction accuracy when the mechanical outputs are expressed as relative values of muscle power (i.e., W/kg). Indeed, when normalized by the subjects' body mass, all the relative measures were shown to be much more related to JSH than the absolute power values ($R^2 \approx 0.75$ vs. 0.52, respectively; for PP, MPP and MPUPV in all loading conditions). This finding is in line with a series of previous studies, which demonstrated that the relative power outputs are strongly related to actual performance in numerous sports disciplines.[2-5, 27] For this reason, Baker and Nance[28] suggested that special attention be given to increasing the power per kilogram of body mass of athletes (specifically, the power/kg produced during jump squats) when attempting to improve their maximal speed capacity. Accordingly, Loturco et al.[2] stated that "when a given subject performs a jump squat, she/he has to jump lifting up the total mechanical system (i.e., weighted bar + body mass)", which necessarily implies neuromechanical outcomes already adjusted for individual body mass. Therefore, it is highly plausible to assume that athletes with greater values of relative power also have a superior ability to accelerate their own body weight throughout a jump squat execution,[2, 3, 29] achieving higher velocities at takeoff and, thus, higher heights during the jumps.

An identical pattern was also observed for the absolute force outputs (i.e., PF, MPF and MFUP), which presented a sharp increase in their relationships with JSH when normalized by the athletes' body mass (Table V). This statistical similarity is quite reasonable, since the force outcomes are directly involved in the power calculation (i.e., *Power = Force x Velocity*). Therefore, it seems that all measures examined here are consistently associated with jump squat performance, and this is independent of the phase of the ballistic lifting used to calculate the mechanical value (i.e., peak or mean propulsive phase) and the loading condition (i.e., 40, 60 or 80% of body mass). Possibly, the particularities of each specific approach might work to balance these equivalent relationships. Although the peak velocity (variable used to calculate PP/PF) is widely recognized as a very-precise predictor of vertical jump performance,[17, 30, 31] it reflects only the final phase of the ground-based movement. On the other hand, in their calculation, MPP and MPPUP consider "mean-related values of velocity" (i.e., mean propulsive velocity),[9, 13, 21] which might better represent the overall shape of the force-velocity curve. It is important to note that this mechanical profile has a central role in determining the total impulse of the movement[32] (i.e., integral of force over time) and this dynamic variable is entirely related to the jump height.[33]

Predictably, the power male track and field group - composed of athletes able to apply high forces at high velocity (i.e., sprinters and jumpers) - presented superior levels of relative muscle power when compared to all other analyzed groups of athletes. Cronin and Hansen[34] also found similar evidence in elite rugby athletes, reporting that the faster players were equally capable of producing higher outputs of relative muscle power during loaded jump squats. Remarkably, the same did not occur with the power female track and field group, which is possibly connected to gender differences, as it is known that women perform worse than men in power-related motor tasks.[35] Nevertheless, it should be emphasized that the subjects involved in this study are athletes at the extreme of human performance (i.e., Olympic athletes) and, accordingly, all of them present highly developed physical qualities. Another important point to be considered is the sensitivity level of the neuromechanical marker. Whereas the relative muscle power measures (i.e., MPPR, MPPUPR and PPR) might discriminate the more powerful athletes (i.e., power male track and field group), the relative force outputs (i.e., PFR, MPFR and MPFUR) may not distinguish among the different groups of sports disciplines. Conceivably, the integration between force and velocity in its calculation makes power a more sensitive indicator of neuromuscular performance than the force output, which depends directly on a scalar variable (i.e., a given mass) to calculate its magnitude. For this reason, coaches and sport scientists are suggested to prioritize the power-related measurements to evaluate and discriminate top-level athletes.

Summarizing, the data presented here clearly demonstrate that all relative power measures (i.e., MPP, MPPUP and PP) can be equally used to assess and train elite athletes in exercises executed under ballistic conditions (i.e., jump squats). This fact can be confirmed by the similar prediction power (in relation to the JSH) ($R^2 \approx 0.75$) and by the absence of significant differences between the residual analysis of these three related measures (Table VI). Importantly, to improve their validity as performance parameters, these mechanical outputs must be normalized by the subjects' body mass. After considering these aspects, sport professionals can accurately use the relative values of MPP, MPPUP and PP in their daily training and assessment routines.

This study is inherently limited by its cross-sectional design, which impairs causal inference due to the absence of a controlled temporal sequence. In this regard, it is crucial to conduct prospective investigations to observe whether the predictive power of MPP, MPPUP and PP (in relation to JSH) remain the same after a strength-power training period. Furthermore, to reinforce our findings, we recommend examination of the validity of these distinct mechanical measures in other specific populations (i.e., moderately trained subjects) and ballistic exercises (i.e., bench throw and push press).

Conclusions

The literature concerning the assessment of the most suitable measure of muscle power to predict functional performance (e.g., sprinting and jumping abilities) and its determining factors (jump squat performance) is far from consensus. In theory, PP measurement is more closely related to performance in ballistic exercises, while MPP is more related to performance in traditional non-ballistic exercises. In applied settings, for practical reasons, it would be worth using the same power output expression to allow for concise comparisons between neuromechanical performances in different exercise modes (e.g., half squat and jump squat). The results of this study clearly show that the MPP has similar capacity to predict jump height in jump squats as the peak-related power values (PP and MPUP). Although sport scientists can use all three power measures for jump squat testing, the MPP might be an advantageous and smart option, due to its adequacy to reflect the neuromuscular potential of the subjects not only in ballistic, but also in non-ballistic exercises. Collectively, our findings permit suggesting the unification of muscle power assessments using the MPP values in both modes of strength-power exercises.

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FIGURE CAPTION

Figure 1. Linear regression between the power related variables and respective jump squat height in the load corresponding to 40% of the athlete's body mass.

Figure 2. Linear regression between the power related variables and respective jump squat height in the load corresponding to 60% of the athlete's body mass.

Figure 3. Linear regression between the power related variables and respective jump squat height in the load corresponding to 80% of the athlete's body mass.

Table I - Comparison of the jump squat height (JSH) and power-related variables among the athletic groups.

Group	Load (% BM)	JSH (cm)	MPUP (W)	MPP (W)	PP (W)
	40%	26.48 ± 4.27¶*	504.4 ± 131.7¥+*	489.6 ± 125.3¥+*	1064.7 ± 243.7§+*†
Combat	60%	22.67 ± 3.48*	613.3 ± 164.3¥+*	595.7 ± 155.7¥+*†	1340.2 ± 313.5+*†
Sports	80%	19.42 ± 3.13*	659.4 ± 177.5¥+*	641.7 ± 170.2¥+*	1531.0 ± 365.2¥+*†
	40%	23.22 ± 5.47$+*	411.4 ± 117.9$¥+	399.2 ± 112.9$¥+	828.2 ± 226.7$¥+‡
Endurance	60%	20.08 ± 4.57+*	510.5 ± 124.5$¥+	496.9 ± 119.5$¥+	1061.4 ± 264.0$¥+‡
Runners	80%	17.59 ± 3.68*	573.6 ± 143.8$¥+	558.9 ± 137.6$¥+	1266.2 ± 332.9¥+‡
	40%	27.16 ± 2.39¶*	535.8 ± 88.7+#*	517.2 ± 84.0+#*	1077.3 ± 147.9+*†
Futsal	60%	23.39 ± 2.28¶*	673.0 ± 106.1+#*	648.5 ± 101.0+#*	1393.8 ± 170.4+*
	80%	19.89 ± 2.05¶*	733.0 ± 118.2+#*	706.6 ± 111.9+#*	1582.7 ± 194.3+*
	40%	21.27 ± 2.50+*¤	428.1 ± 65.2¥+*†	412.0 ± 61.6¥+*†	850.8 ± 158.8¥+‡*†
Female	60%	18.84 ± 1.94+*	536.7 ± 81.8¥+*†	517.8 ± 78.9¥+*†	1094.3 ± 192.7¥+*†
Judo	80%	16.03 ± 1.72+*	590.1 ± 110.6¥+*†	571.1 ± 105.6¥+*†	1236.3 ± 204.1¥+‡*†
	40%	25.63 ± 2.04*	644.2 ± 123.7#	622.8 ± 116.4#	1258.7 ± 175.9#
Male	60%	22.10 ± 1.80*	778.0 ± 123.6#	755.0 ± 119.2#	1664.7 ± 256.0#
Judo	80%	18.85 ± 1.35*	854.1 ± 106.3#	841.9 ± 105.3#	1925.6 ± 267.9#
	40%	28.60 ± 3.76	671.5 ± 118.5#¤	648.8 ± 115.0#¤	1337.8 ± 251.5#
Rugby 7s	60%	24.72 ± 3.89	842.5 ± 141.3#¤‡	813.7 ± 135.2#¤‡	1749.4 ± 363.7#
	80%	20.91 ± 3.47¶#*	898.1 ± 163.8#	869.7 ± 156.7#	1958.7 ± 398.1#
	40%	26.52 ± 2.81*	555.7 ± 82.4§#*	541.6 ± 78.7§¶#*	1194.0 ± 162.9§¶#*
Strikers	60%	22.55 ± 2.73*	686.8 ± 105.7§#*	668.5 ± 100.6§#*	1532.2 ± 227.5§¶#*
	80%	19.31 ± 2.88*	752.1 ± 126.4§#*	730.7 ± 117.8#*	1760.7 ± 303.4§¶#*
	40%	24.76 ± 1.88*	541.9 ± 105.0*	526.6 ± 98.8*	1142.1 ± 199.5*
Tennis	60%	20.93 ± 1.82*	665.6 ± 132.8*	646.7 ± 124.5*	1438.4 ± 230.4*
	80%	17.96 ± 1.64*	754.7 ± 168.41*#	722.6 ± 152.4#*	1691.4 ± 315.1#*
	40%	24.83 ± 3.78*	427.9 ± 82.6*†	416.0 ± 79.6*†	928.9 ± 185.3*†
P T & F	60%	21.26 ± 3.37*	526.9 ± 107.9*†	512.2 ± 102.2*†	1177.1 ± 220.6*†
Female	80%	17.75 ± 2.71	550.9 ± 111.9*†	538.7 ± 106.6*†	1286.6 ± 210.8*†
	40%	31.23 ± 3.36	690.0 ± 98.1§	669.5 ± 93.2§	1420.6 ± 183.1§
P T & F	60%	27.28 ± 3.56	855.4 ± 133.3§	830.6 ± 126.3§	1828.7 ± 267.0§
Male	80%	23.65 ± 3.11	953.2 ± 161.7§	924.8 ± 153.5§	2111.7 ± 320.6§
	40%	25.81 ± 3.69*	638.9 ± 77.2§	621.7 ± 74.9§	1366.3 ± 184.7§
Volleyball	60%	22.15 ± 3.26*	785.0 ± 104.8§	764.4 ± 99.4§	1733.8 ± 226.5§
	80%	19.15 ± 3.36*	836.5 ± 129.6§	813.4 ± 115.1§	1967.8 ± 267.2§

BM: body mass; combat sports: karate and taekwondo; strikers: boxing and muay-thai; P T & F: power track & field; MPUP: mean power until peak velocity; MPP: mean propulsive power; PP: peak power.

Symbols represent statistical significant difference ($P < 0.05$) from §endurance runners; $futsal; ¶female judo; ¥male judo; +rugby 7s; ¤strikers; ‡tennis; #P T & F female; *P T & F male; †volleyball.

Table II - Comparison of the power-related variables relative to athlete's body mass (BM) among the athletic groups.

Group	Load (% BM)	MPUPR (W·kg^{-1})	MPPR (W·kg^{-1})	PPR (W·kg^{-1})
Combat Sports	40%	7.41 ± 1.19*	7.19 ± 1.13*	15.68 ± 2.27*
	60%	9.00 ± 1.51*	8.75 ± 1.43*	19.70 ± 2.65*
	80%	9.67 ± 1.50*	9.42 ± 1.45*	22.50 ± 3.13*
Endurance Runners	40%	6.92 ± 1.33^{+}*	6.72 ± 1.26^{+}*	13.94 ± 2.51^{+}*
	60%	8.64 ± 1.46^{+}*	8.41 ± 1.40^{+}*	17.91 ± 3.03^{+}*
	80%	9.71 ± 1.71*	9.46 ± 1.65*	21.37 ± 3.90*
Futsal	40%	7.55 ± 0.88*	7.24 ± 0.81*	15.22 ± 1.50*
	60%	9.50 ± 1.07*	9.15 ± 0.99*	19.73 ± 1.78*
	80%	10.36 ± 1.27*	9.98 ± 1.15*	22.39 ± 1.91*
Female Judo	40%	6.80 ± 0.85^{+}*	6.54 ± 0.81^{+}*	13.42 ± 1.62$^{+¤}$*
	60%	8.54 ± 1.26^{+}*	8.24 ± 1.16^{+}*	17.26 ± 1.66$^{+¤}$*
	80%	9.34 ± 1.34*	9.04 ± 1.24*	19.55 ± 1.86$^{+¤}$*
Male Judo	40%	7.61 ± 0.99*	7.36 ± 0.91*	14.93 ± 1.35*
	60%	9.21 ± 0.87*	8.94 ± 0.83*	19.69 ± 1.59*
	80%	10.27 ± 0.84*	10.00 ± 0.80*	22.84 ± 1.85*
Rugby 7s	40%	8.28 ± 1.06*†	8.00 ± 1.03*	16.47 ± 2.31*
	60%	10.42 ± 1.52*‡†	10.06 ± 1.43*‡†	21.56 ± 3.73*
	80%	11.12 ± 1.88*	10.77 ± 1.88*	24.17 ± 4.32*
Strikers	40%	7.43 ± 0.58*	7.24 ± 0.56*	16.05 ± 1.89*
	60%	9.21 ± 0.98*	8.96 ± 0.93*	20.64 ± 2.77*
	80%	10.04 ± 1.05*	9.76 ± 0.96*	23.63 ± 2.98*
Tennis	40%	7.03 ± 0.92*	6.83 ± 0.84*	14.82 ± 1.65*
	60%	8.64 ± 1.27*	8.40 ± 1.16*	18.70 ± 2.09*
	80%	9.64 ± 1.48*	9.35 ± 1.29*	21.93 ± 2.72*
P T & F Female	40%	7.32 ± 0.97*	7.12 ± 0.91*	15.89 ± 2.17*
	60%	9.03 ± 1.39*	8.77 ± 1.29*	20.17 ± 2.69*
	80%	9.44 ± 1.47*	9.23 ± 1.37*	22.07 ± 2.37*
P T & F Male	40%	9.02 ± 1.07	8.75 ± 0.99	18.59 ± 2.02
	60%	11.20 ± 1.59	10.87 ± 1.51	23.95 ± 3.30
	80%	12.47 ± 1.86	12.10 ± 1.78	27.66 ± 3.92
Volleyball	40%	6.87 ± 0.96*	6.69 ± 0.92*	14.72 ± 2.41*
	60%	8.45 ± 1.32*	8.23 ± 1.25*	18.66 ± 2.86*
	80%	9.00 ± 1.51*	8.75 ± 1.39*	21.12 ± 2.90*

Combat sports: karate and taekwondo; strikers: boxing and muay-thai; P T & F: power track & field; MPUPR: mean power until peak velocity relative to body mass; MPPR: mean propulsive power relative to body mass; PPR: peak power relative to body mass.

Symbols represent statistical significant difference ($P < 0.05$) from $^{+}$rugby 7s; $^{¤}$strikers; ‡tennis; *P T & F male; †volleyball.

Table III - Comparison of the force-related variables among the athletic groups.

Group	Load (% BM)	MFUP (N)	MPF (N)	PF (N)
Combat Sports	40%	435.4 ± 92.3$^{¥+*†}$	412.9 ± 85.1$^{¥+*†}$	508.2 ± 104.9$^{¥+*†}$
	60%	601.2 ± 125.2$^{¥+*†}$	568.5 ± 115.7$^{¥+*†}$	698.6 ± 140.3$^{¥+*†}$
	80%	742.8 ± 158.4$^{¥+*†}$	701.3 ± 146.5$^{¥+*†}$	868.5 ± 183.2$^{¥+*†}$
Endurance Runners	40%	370.3 ± 73.0$^{\$¥+}$	350.9 ± 69.0$^{\$¥+}$	423.0 ± 80.7$^{\$¥+}$
	60%	515.0 ± 84.4$^{\$¥+}$	487.6 ± 80.2$^{\$¥+}$	588.0 ± 103.1$^{\$¥+}$
	80%	643.2 ± 105.7$^{\$¥+}$	607.5 ± 97.1$^{\$¥+}$	754.0 ± 135.4$^{\$¥+}$
Futsal	40%	459.1 ± 53.1$^{¥+\#*†}$	431.2 ± 50.4$^{¥+\#*†}$	530.2 ± 51.9$^{¥+\#*†}$
	60%	644.1 ± 66.2$^{¥+\#*†}$	601.7 ± 63.4$^{¥+\#*†}$	743.0 ± 71.2$^{¥+\#*†}$
	80%	792.1 ± 81.6$^{¥+\#*†}$	739.3 ± 79.0$^{¥+\#*†}$	916.1 ± 90.0$^{¥+\#*†}$
Female Judo	40%	406.1 ± 58.0$^{¥+*†}$	380.0 ± 52.2$^{¥+*†}$	462.8 ± 75.2$^{¥+*†}$
	60%	567.2 ± 68.5$^{¥+*†}$	529.9 ± 66.3$^{¥+*†}$	641.2 ± 97.6$^{¥+¤*†}$
	80%	711.1 ± 103.0$^{¥+*†}$	664.2 ± 96.9$^{¥+*†}$	810.3 ± 114.6$^{¥+¤*†}$
Male Judo	40%	549.5 ± 78.4$^{\#}$	519.8 ± 73.4$^{\#}$	629.9 ± 91.5$^{\#}$
	60%	754.8 ± 92.7$^{\#}$	714.8 ± 89.6$^{\#}$	884.7 ± 111.4$^{\#}$
	80%	952.6 ± 101.5$^{\#}$	902.6 ± 102.6$^{\#}$	1113.4 ± 146.5$^{\#}$
Rugby 7s	40%	545.8 ± 73.6$^{\#¤}$	515.3 ± 70.8$^{\#}$	627.5 ± 99.6$^{\#}$
	60%	767.7 ± 91.5$^{\#¤}$	722.3 ± 85.5$^{\#¤}$	879.8 ± 129.0$^{\#}$
	80%	933.9 ± 104.4$^{\#}$	878.9 ± 96.4$^{\#}$	1077.1 ± 145.5$^{\#}$
Strikers	40%	477.4 ± 65.7$^{§\#†}$	455.4 ± 61.5$^{§\#†}$	558.8 ± 79.0$^{§\#†}$
	60%	663.9 ± 81.9$^{§\#†}$	630.4 ± 75.8$^{§\#†}$	782.1 ± 93$^{§\#}$
	80%	831.8 ± 109.1$^{§\#}$	785.7 ± 98.9$^{§\#†}$	989.8 ± 135.9$^{§\#}$
Tennis	40%	483.3 ± 65.0$^{§\#}$	459.0 ± 60.5$^{§\#}$	556.9 ± 75.8$^{§\#}$
	60%	672.8 ± 79.8$^{§\#}$	637.0 ± 74.7$^{§\#}$	782.6 ± 83.5$^{§\#}$
	80%	843.2 ± 120.2$^{§\#}$	795.0 ± 107.5$^{§\#}$	985.5 ± 128.8$^{§\#}$
P T & F Female	40%	377.6 ± 44.3*†	359.3 ± 42.2*†	447.8 ± 57.3*†
	60%	519.3 ± 59.8*†	492.4 ± 55.6*†	614.0 ± 75.7*†
	80%	632.9 ± 65.9*†	601.6 ± 61.5*†	747.3 ± 78.8*†
P T & F Male	40%	529.0 ± 54.4§	503.8 ± 50.4§	621.9 ± 70.0§
	60%	730.0 ± 81.8§	693.5 ± 75.0§	860.8 ± 101.7§
	80%	912.1 ± 100.9§	863.3 ± 92.3§	1075.0 ± 120.6§
Volleyball	40%	573.9 ± 50.3§	544.9 ± 48.7§	665.1 ± 63.1§
	60%	790.3 ± 71.1§	748.9 ± 69.4§	914.9 ± 85.5§
	80%	972.9 ± 87.4§	917.5 ± 82.6§	1139.0 ± 119.4§

BM: body mass; combat sports: karate and taekwondo; strikers: boxing and muay-thai; P T & F: power track & field; MFUP: mean force until peak velocity; MPF: mean propulsive force; PF: peak force. Symbols represent statistical significant difference ($P < 0.05$) from §endurance runners; $^{\$}$futsal; $^{¥}$male judo; $^{+}$rugby 7s; $^{¤}$strikers; $^{\#}$P T & F female; * P T & F male; †volleyball.

Table IV - Comparison of the force-related variables relative to athlete's body mass (BM) among the athletic groups.

Group	Load (% BM)	MFUPR ($N \cdot kg^{-1}$)	MPFR ($N \cdot kg^{-1}$)	PFR ($N \cdot kg^{-1}$)
Combat Sports	40%	6.39 ± 0.39*	6.06 ± 0.37*	7.47 ± 0.58*
	60%	8.83 ± 0.50*	8.36 ± 0.49*	10.28 ± 0.61*
	80%	10.89 ± 0.56*	10.30 ± 0.57*	12.75 ± 0.86*
Endurance Runners	40%	6.26 ± 0.53^{+}*	5.93 ± 0.49*	7.17 ± 0.69*
	60%	8.74 ± 0.50^{+}*	8.27 ± 0.49^{+}*	9.96 ± 0.72*
	80%	10.91 ± 0.60*	10.31 ± 0.57*	12.77 ± 0.95*
Futsal	40%	6.48 ± 0.31*	6.09 ± 0.27*	7.50 ± 0.34*
	60%	9.12 ± 0.50*	8.51 ± 0.43*	10.53 ± 0.74*
	80%	11.21 ± 0.59*	10.46 ± 0.50*	12.97 ± 0.78*
Female Judo	40%	6.42 ± 0.36*	6.01 ± 0.32*	7.30 ± 0.45*
	60%	9.00 ± 0.58*	8.40 ± 0.50*	10.13 ± 0.59*
	80%	11.24 ± 0.56*	10.50 ± 0.49*	12.81 ± 0.50*
Male Judo	40%	6.51 ± 0.46	6.15 ± 0.40*	7.47 ± 0.70
	60%	8.95 ± 0.42	8.47 ± 0.40	10.5 ± 0.63
	80%	11.31 ± 0.30	10.71 ± 0.33	13.20 ± 0.84
Rugby 7s	40%	6.73 ± 0.40†	6.35 ± 0.41†	7.72 ± 0.66
	60%	9.49 ± 0.76†	8.93 ± 0.69†	10.87 ± 1.17
	80%	11.56 ± 0.95†	10.88 ± 0.89†	13.32 ± 1.34
Strikers	40%	6.39 ± 0.28*	6.10 ± 0.26*	7.50 ± 0.56*
	60%	8.93 ± 0.60*	8.48 ± 0.53*	10.66 ± 0.98*
	80%	11.16 ± 0.59*	10.55 ± 0.51*	13.33 ± 1.10*
Tennis	40%	6.28 ± 0.40*	5.96 ± 0.34*	7.24 ± 0.54*
	60%	8.76 ± 0.64*	8.29 ± 0.53*	10.21 ± 0.73*
	80%	10.95 ± 0.74*	10.33 ± 0.58*	12.82 ± 0.86*
P T & F Female	40%	6.49 ± 0.36*	6.17 ± 0.31*	7.70 ± 0.60*
	60%	8.94 ± 0.62*	8.47 ± 0.51*	10.56 ± 0.82*
	80%	10.90 ± 0.65*	10.35 ± 0.53*	12.86 ± 0.71*
P T & F Male	40%	6.91 ± 0.41	6.58 ± 0.37	8.13 ± 0.62
	60%	9.54 ± 0.67	9.06 ± 0.61	11.24 ± 0.87
	80%	11.91 ± 0.77	11.28 ± 0.70	14.05 ± 1.04
Volleyball	40%	6.15 ± 0.37*	5.84 ± 0.35*	7.14 ± 0.69*
	60%	8.47 ± 0.64*	8.02 ± 0.57*	9.81 ± 0.89*
	80%	10.42 ± 0.63*	9.82 ± 0.56*	12.19 ± 0.87*

Combat sports: karate and taekwondo; strikers: boxing and muay-thai; P T & F: power track & field; MFUPR: mean force until peak velocity relative to body mass; MPFR: mean propulsive force relative to body mass; PFR: peak force relative to body mass. Symbols represent statistical significant difference ($P < 0.05$) from $^{+}$rugby 7s; *P T & F male; †volleyball.

Table V – Correlations (r values obtained from Pearson's test) between force-related variables and respective jump squat heights (JSH) at loads corresponding to 40%, 60%, and 80% of the athletes' body mass.

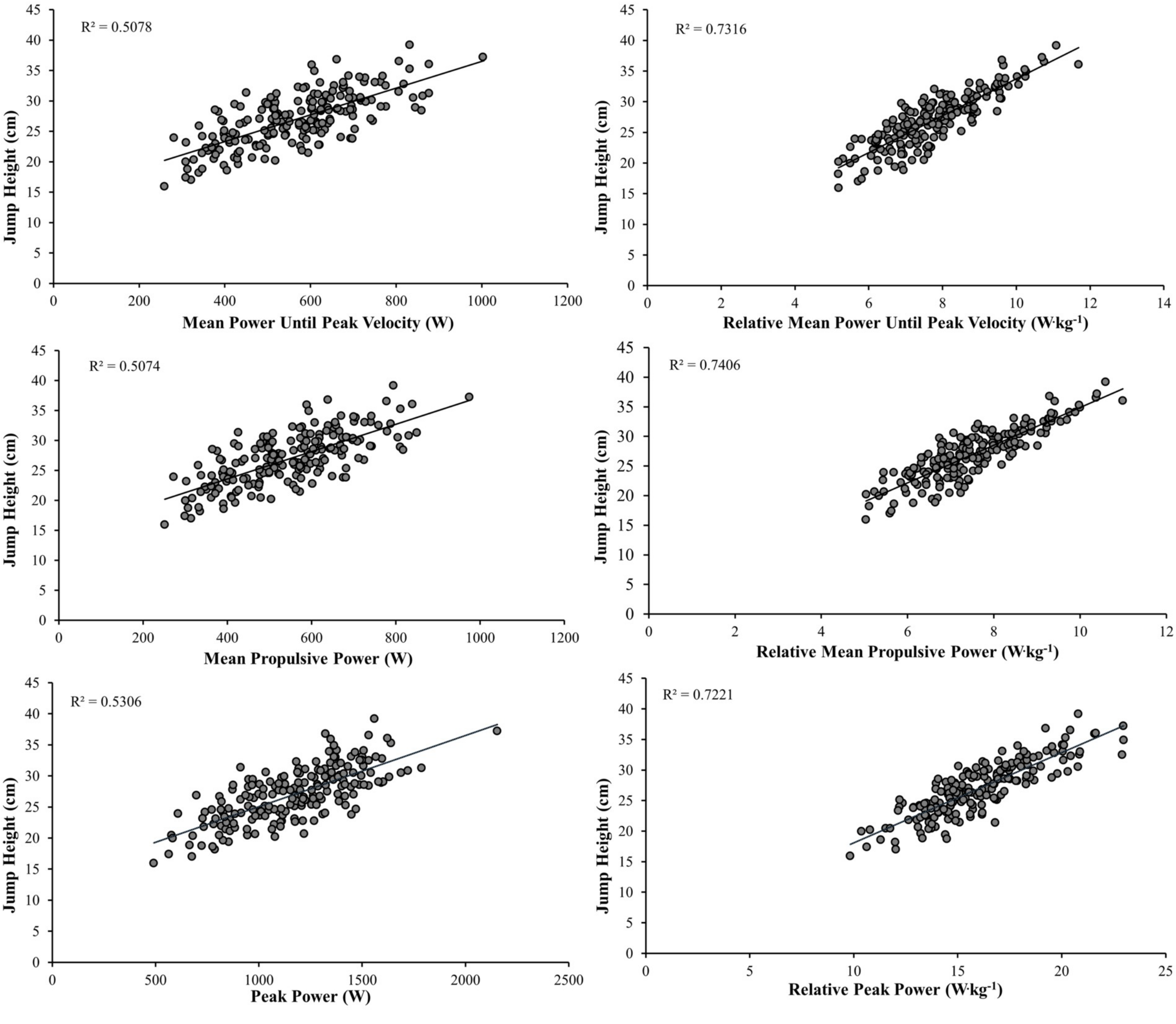
	PF	**PFR**	**MPF**	**MPFR**	**MFUP**	**MFUPR**
JSH 40%	0.54	0.70	0.50	0.76	0.50	0.74
JSH 60%	0.54	0.67	0.50	0.71	0.51	0.68
JSH 80%	0.51	0.66	0.48	0.71	0.49	0.71

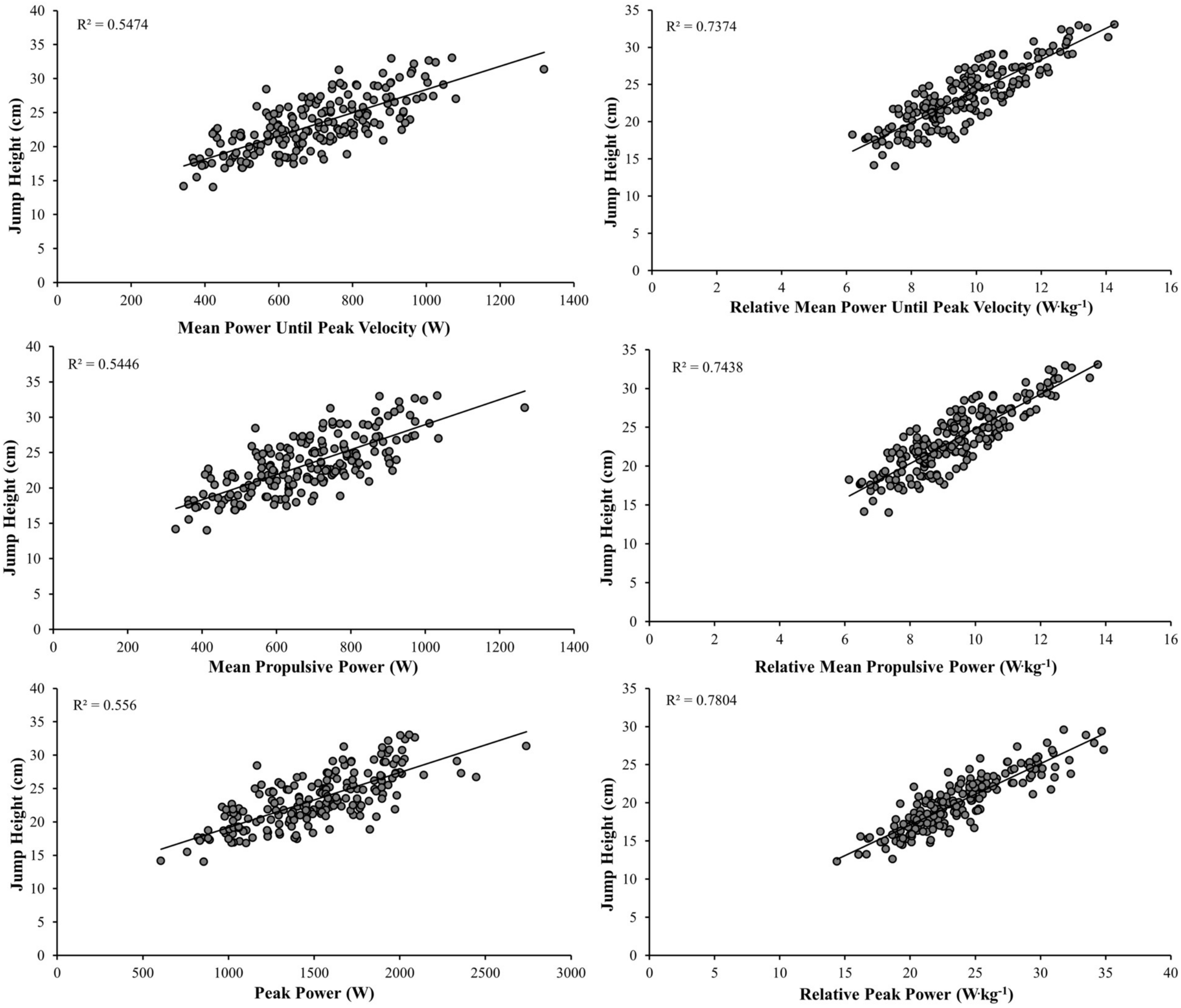
PF: peak force; PFR: peak force relative to body mass; MPF: mean propulsive force; MPFR: mean propulsive force relative to body mass; MFUP: mean force until peak velocity; MFUPR: mean force until peak velocity relative to body mass; $P < 0.01$ for all correlations.

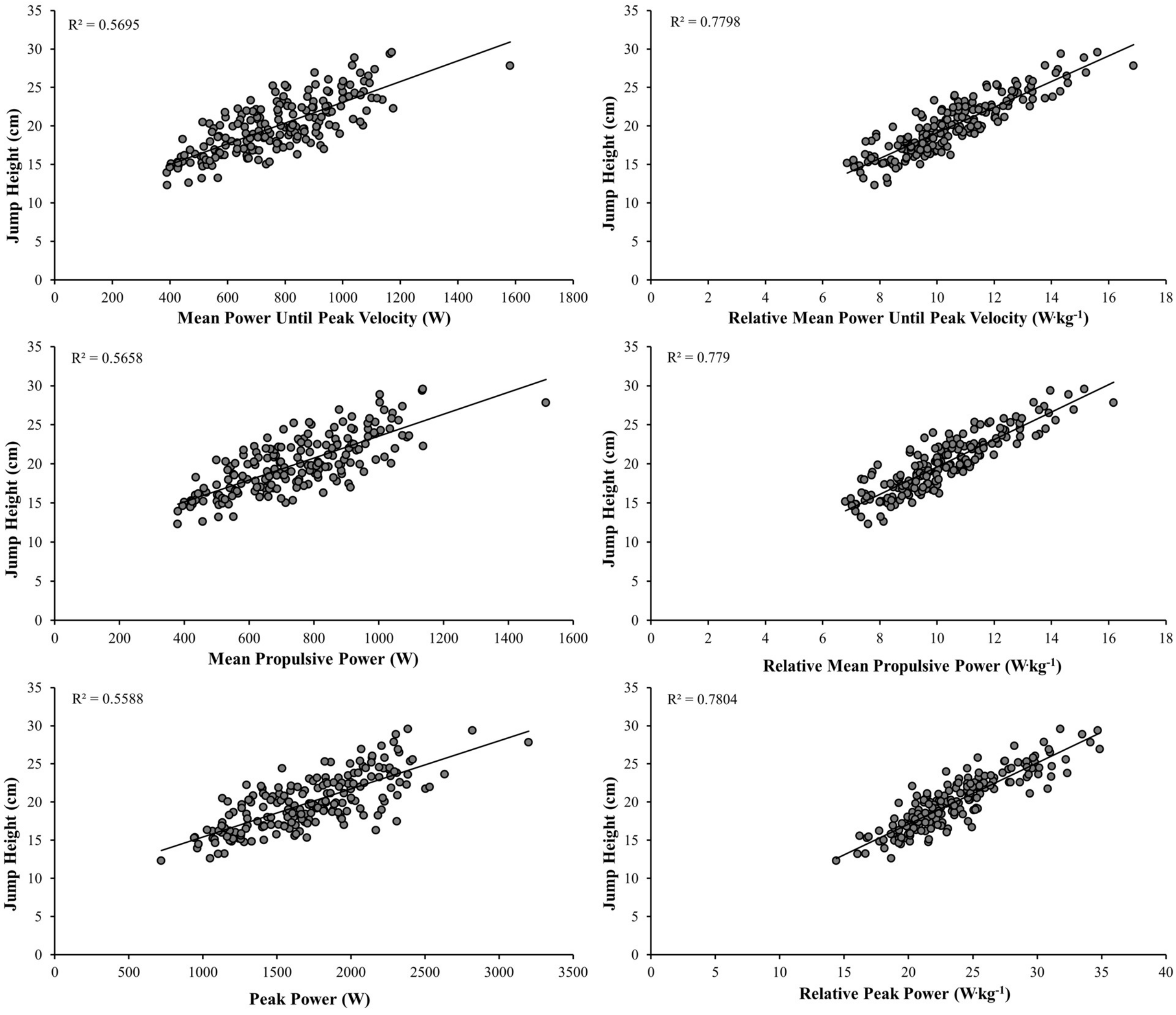
Table VI - Residual analysis from the linear regression between the power-related variables and the respective jump squat heights (JSH) at the loads corresponding to 40%, 60%, and 80% of the athlete's body mass.

	MPUP	**MPP**	**PP**	**MPUPR**	**MPPR**	**PPR**
JSH 40%	2.48 ± 1.75	2.48 ± 1.75	2.46 ± 1.65	1.79 ± 1.35	1.74 ± 1.35	1.84 ± 1.34
JSH 60%	2.25 ± 1.49	2.26 ± 1.50	2.17 ± 1.56	1.71 ± 1.15	1.68 ± 1.15	1.58 ± 1.19
JSH 80%	1.92 ± 1.33	1.93 ± 1.33	1.95 ± 1.34	1.36 ± 0.96	1.35 ± 0.99	1.31 ± 1.03

MPUP: mean power until peak velocity; MPP: mean propulsive power; PP: peak power; MPUPR: mean power until peak velocity relative to body mass; MPPR: mean propulsive power relative to body mass; PPR: peak power relative to body mass.


R² = 0.5078
Jump Height (cm)
Mean Power Until Peak Velocity (W)
R² = 0.7316
Jump Height (cm)
Relative Mean Power Until Peak Velocity (W·kg⁻¹)
R² = 0.5074
Jump Height (cm)
Mean Propulsive Power (W)
R² = 0.7406
Jump Height (cm)
Relative Mean Propulsive Power (W·kg⁻¹)
R² = 0.5306
Jump Height (cm)
Peak Power (W)
R² = 0.7221
Jump Height (cm)
Relative Peak Power (W·kg⁻¹)


R² = 0.5474
Jump Height (cm)
Mean Power Until Peak Velocity (W)
R² = 0.7374
Jump Height (cm)
Relative Mean Power Until Peak Velocity (W·kg⁻¹)
R² = 0.5446
Jump Height (cm)
Mean Propulsive Power (W)
R² = 0.7438
Jump Height (cm)
Relative Mean Propulsive Power (W·kg⁻¹)
R² = 0.556
Jump Height (cm)
Peak Power (W)
R² = 0.7804
Jump Height (cm)
Relative Peak Power (W·kg⁻¹)


R² = 0.5695
Jump Height (cm)
Mean Power Until Peak Velocity (W)
R² = 0.7798
Jump Height (cm)
Relative Mean Power Until Peak Velocity (W·kg⁻¹)
R² = 0.5658
Jump Height (cm)
Mean Propulsive Power (W)
R² = 0.779
Jump Height (cm)
Relative Mean Propulsive Power (W·kg⁻¹)
R² = 0.5588
Jump Height (cm)
Peak Power (W)
R² = 0.7804
Jump Height (cm)
Relative Peak Power (W·kg⁻¹)