



ARE VERTICAL JUMP HEIGHT AND POWER OUTPUT CORRELATED TO PHYSICAL PERFORMANCE IN DIFFERENT SPORTS? AN ALLOMETRIC APPROACH

original paper

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JULIANO DAL PUPO¹, JONATHAN ACHE-DIAS², RAFAEL LIMA KONS¹, DANIELE DETANICO¹

¹ Biomechanics Laboratory, Centre of Sports, Federal University of Santa Catarina, Florianópolis, Brazil

² Research Group on Technology, Sport and Rehabilitation, Catarinense Federal Institute, Araquari, Brazil

ABSTRACT

Purpose. This study aimed to analyse the relationship between vertical jump parameters – jump height (JH), peak power output (PPO), and mean power output (MPO) – and specific physical performance in different sports using the allometric approach. In this sense, it was verified whether scaled power output for body mass might have a stronger correlation with physical performance than raw power output.

Methods. The study involved 52 male athletes (21 judokas, 18 futsal players, and 13 sprint runners). They performed the following tests: vertical jumps (countermovement and squat), specific physical tests for judo (Special Judo Fitness Test), repeated sprint ability for futsal players, and sprint running (20 m and 200 m) for runners. A specific allometric exponent for PPO and MPO was established. Pearson's correlation was used to determine the relationship between physical tests and vertical jump parameters for absolute and allometric scales.

Results. Moderate to very large correlations were found between physical performance and JH (r : 0.47–0.87), PPO (r : 0.47–0.75), and MPO (r : 0.49–0.81). Considering power output scaled for body mass, the correlation between jump parameters and physical performance was greater than absolute values, in which the r values ranged 0.46–0.81 for PPO and 0.52–0.84 for MPO.

Conclusions. JH and power output seem to correlate in a similar magnitude with physical performance tests for most variables and sports analysed. From a practical point of view, coaches and physical trainers are encouraged to use JH to monitor training, considering the cost of equipment and practicality.

Key words: sports, body size, allometric scaling, running, martial arts, soccer

Introduction

The ability to generate a high rate of mechanical work by the lower limbs (i.e., mechanical power capability) during a propulsive phase of a ballistic movement is a determinant factor in many sports [1–4]. Therefore, the evaluation of this physical capacity is a common practice among professionals of sports training, usually aiming to monitor training effects and muscle recovery, as well as to predict performance [5–7].

Conventionally, vertical jumps, such as the countermovement jump (CMJ) and squat jump (SJ), have been the most frequently used tests for evaluating lower limb power output in different sports [8–10]. The main reason for this choice is that athletes produce high amounts of

mechanical work over a short duration to displace their body mass during the vertical jump [11]. The mechanical power output generated in CMJ or SJ is considered to be the main indicator of lower limb performance [12]. Alternatively, jump height (JH) has been considered to be a power output indicator *per se* [13].

The power output and JH have been widely used by researchers and practitioners, but there is no consensus about which is the most adequate to represent lower limb performance. Owing to its usability, JH is probably the most used index in vertical jump assessment, but it has been criticized for not being able to represent the lower limb mechanical power capabilities [11, 14, 15]. Another unsolved question concerns the application of the peak or mean power output. The peak

Correspondence address: Rafael Lima Kons, Laboratório de Biomecânica, Centro de Desportos, Universidade Federal de Santa Catarina, 88040-900 / Florianópolis – SC, Brazil, e-mail: rafakons0310@gmail.com

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power output (PPO) obtained during the vertical jump corresponds to a specific moment close to the take-off, while the mean power output (MPO) represents the entire push-off phase [16]. It is known that jumping performance is determined by the centre of mass velocity at the end of the push-off – a decisive moment in which the power output is maximal. On the other hand, from a mechanical point of view, dynamic principles show that the change in the momentum of a system depends directly on the net vertical impulse applied over the entire movement. Therefore, only focusing on the instantaneous peak value corresponds to a very specific anatomical and neuromuscular configuration and may not represent the whole dynamic lower limb capability. A previous study by Ache-Dias et al. [17] revealed that PPO (directly measured by using a force platform) and MPO (obtained by equation regressions) did not classify the athletes equally; however, it is unknown which index is most representative of sports performance.

Another concern when using vertical jump assessment is the influence of body dimensions, especially body mass. The power output is commonly normalized or scaled for body mass by using a ratio standard or allometric adjustment. However, it has been shown that scaling methods are highly sport-specific [18], thus not allowing for the use of a single exponent or model in vertical jump assessment. This is probably because athletes of different sports present different neuromuscular demands due to specific training [11]. In this sense, the sensitivity to monitor the neuromuscular status with vertical jump parameters is probably higher when an adequate and sport-specific scaling method is applied. Innumerable parameters are available to monitor training, but very few of them have strong scientific evidence supporting their use in terms of ecological validity, i.e., the ability to replicate the athlete's event/competition.

Thus, the objective of the present study was to analyse the relationship between vertical jump parameters and specific physical performance in different sports (judo, futsal, and sprint running) using the allometric approach. In this sense, it was verified whether the scaled power output might have a stronger correlation with physical performance than the raw power values. We hypothesized that all jump parameters presented a good relationship with specific physical performance, but the magnitude of correlations depended on the scaling method used.

Material and methods

Participants

A total of 52 male athletes participated in this study: 21 judokas (height: 174 ± 7.5 cm; body mass: 71.4 ± 11.6 kg; age: 19.9 ± 2.7 years), 18 futsal players (height: 170 ± 6.0 cm; body mass: 66.34 ± 7.7 kg; age: 17.9 ± 1.0 years), and 13 100- and 200-m sprint runners (height: 176.93 ± 7.21 cm; body mass: 69.77 ± 5.93 kg; age: 20.89 ± 3.23 years). The participants attended training sessions at least 5 days a week and had a minimum of 6 years of experience in their sport. They were competing at a state or national level. No athletes reported injuries or other conditions that impeded them from maximal physical performance. Before the assessments, all subjects were informed about the study procedures.

Procedures

The athletes of 3 sports (judo, futsal, and sprint running) were evaluated in 2 situations: (1) performing vertical jump tests (CMJ and SJ); and (2) performing specific physical tests: the Special Judo Fitness Test (SJFT) for judo, repeated sprint ability (RSA) for futsal players, and sprints of 20 m and 200 m (time trial) for sprint runners. These tests were selected because they were considered to be capable of representing the specific physical demands of the analysed sports.

The evaluations were performed during the competitive period of the athletes. All assessments were carried out in the afternoon and lasted an average of 2 hours. The vertical jumps (CMJ and SJ) were performed in a randomized order, but before the sport-specific tests, which took place at least 1 hour later.

Vertical jump assessment

Before the vertical jump assessment, the subjects participated in a familiarization/warm-up, involving 30 seconds of jumping on a trampoline, 3 series of 10 jumps on the ground, and 5 submaximal CMJs. The athletes performed the CMJ and SJ protocols. For the CMJ, they started from a static standing position and were instructed to perform a countermovement (descent phase) followed by a rapid and vigorous extension of the lower limb joints (ascent phase). During the jump, the participants were asked to keep their trunks as vertical as possible and their hands remained on their hips. The athletes were then instructed to jump as high as possible. In the SJ, the subjects started the jump from

a static position, with the knees at an angle of about 90°, the trunk as vertical as possible, and the hands on the waist. The jump was performed without any counter-movement. The vertical jumps were performed on a piezoelectric force platform (9290AD, 500 Hz, Kistler, Quattro Jump, Winterthur, Switzerland). Each participant completed 5 jumps with a rest interval of 1 minute in between; the 3 best attempts were retained for analysis. For data analysis, first the acceleration curve was calculated by dividing ground reaction forces by the body mass of the subject. Next, an integration of the acceleration curve was used to obtain the velocity and double integration was performed to obtain the displacement curve. The greatest vertical centre of mass displacement was taken as the JH. Power output was calculated by multiplying the ground reaction force by velocity at the positive phase of the jump, and the MPO and PPO were considered for analysis.

Special Judo Fitness Test

The SJFT proposed by Sterkowicz [19] was used to describe the specific physical performance of judokas. First, the athletes performed 5-minute warm-ups, which consisted of jogging, judo falling techniques (*ukemi*), and repetitive throwing techniques without falling (*uchi-komi*). Subsequently, 3 athletes of similar body mass and height performed the SJFT, in accordance with the following protocol: 2 judokas were positioned at a distance of 6 m from each other, while the test executor was positioned 3 m from the judokas to be thrown. The procedure was divided into 3 periods: 15 seconds (A), 30 seconds (B), and 30 seconds (C), with 10-second intervals between the periods. In each period, the executor threw the opponents as many times as possible using the *ippon-seoi-nage* technique. Performance was determined on the basis of the total throws completed during each of the 3 periods (A + B + C). Heart rate was measured immediately after the test and then 1 minute later (Polar® M430, Kempele, Finland). The index was calculated as the sum of heart rate values (immediately after the test and 1 minute later) divided by the total number of throws [19].

Sprint performance

After the warm-up session (5-minute jogging, stretching exercises, and three 30-m progressive sprints), the sprint runners individually performed three 20-m sprints and a 200-m time trial, from a block start at their maximal effort on an official outdoor running

track. A minimum 30-minute period of complete rest was observed between the 20-m sprints and the 200-m time trial. The running time was recorded by 2 electronic photocells (Speed Test 4.0, CEFISE®, Brazil).

Repeated sprint ability assessment

Before the RSA assessment, futsal players performed a warm-up that consisted of 5-minute low-intensity running (jogging), followed by 5 progressive sprints (ca. 25 m). Then, the athletes implemented the RSA protocol as described by Buchheit et al. [20], which consisted of 2 sets of 6 repeated maximal 25-m sprints: (i) repeated straight line sprint (RSL: 6 × 25 m); (ii) repeated shuttle sprint (RSS: 6 × [2 × 12.5 m]) with a 180° change in direction. The participants had 10 seconds of active recovery after each sprint. They were instructed to complete all sprints as fast as possible and strong verbal encouragement was provided during all sprints. The RSA tests (RSL and RSS) were performed over 2 days in a randomized order, on a futsal court, with 2 electronic photocells (Speed Test 4.0, CEFISE®, Brazil) to record the time for the sprints; these were placed 25 m from each other in the RSL and 12.5 m from each other in the RSS. The following variables were obtained from the RSA tests: best time and mean time.

Allometric modelling of power output

The power output obtained from vertical jumps was scaled for body mass by using specific allometric exponents. First, we tested for the better scaling method of MPO and PPO for body mass (BM). Tanner's exceptional circumstance [21, 22] was applied to verify the linearity between MPO or PPO and BM and check whether it was possible to use the ratio standard (MPO or PPO · BM⁻¹) to normalize the power output. Linearity is confirmed (true) when the ratio between the coefficients of variation (CV) of MPO or PPO and BM is equal to the Pearson's correlation coefficient (*r*) established between them (Equation 1).

$$CV_{BM} = CV_{PPO} = r \quad (1)$$

If Tanner's exceptional circumstance was false, log-linear regressions were established for each sport (Equation 2) based on the natural logarithms (ln) of BM (kg) and MPO or PPO, composed of a constant (*a*) and the slope – allometric exponents (*b*).

$$\ln PPO_{ADJ} = (\ln a) + (bx \ln BM) \quad (2)$$

To test the quality of the log-linear regression, the following criteria were used [23]: (a) coefficient of determination (R^2); (b) the distribution normality of the residuals, with the Shapiro-Wilk test; (c) the homoscedasticity of residuals, with Pearson's correlation between the absolute residual and the independent BM (lnBM). After this, scaled MPO or PPO for BM was calculated for each sport and variable, in accordance with Equation 3. Thus, the adjusted MPO (MPO_{ADJ}) or PPO (PPO_{ADJ}) and BM were correlated to test whether the allometric scaling was satisfactory to remove the BM effect.

$$MPO \text{ or } PPO_{ADJ} = MPO \text{ or } PPO \times BM^{-b} \quad (3)$$

Statistical analysis

The normal distribution of the variables was confirmed by the Shapiro-Wilk test. Pearson's linear correlation was used to determine the relationship between specific physical tests and vertical jump parameters (JH, PPO, and MPO) for absolute and allometric modelling scales. We adopted the following criteria to classify the magnitude of correlation (r): 0–0.1 (trivial), 0.1–0.3 (small), 0.3–0.5 (moderate), 0.5–0.7 (large), 0.7–0.9 (very large), and 0.9–1.0 (almost perfect) [24]. All statistical analyses were performed by using the SPSS 17.0 software, with a significance level set at $\alpha = 0.05$.

Ethical approval

The research related to human use has complied with all the relevant national regulations and institutional policies, has followed the tenets of the Declaration of Helsinki, and has been approved by the Federal University of Santa Catarina Human Research Ethics Committee.

Informed consent

Informed consent has been obtained from all individuals included in this study.

Results

Table 1 shows the results of the specific physical tests for each sport.

The results of allometric modelling for power output obtained in the vertical jump are shown in Table 2, in which b is the specific allometric exponent for each power output variable. The Shapiro-Wilk test confirmed the assumption of normally distributed residuals (residual distribution $p > 0.05$) for all variables. The

Table 1. Descriptive values (mean, SD , and CV) of performance in specific physical tests in different sports

Test	Mean \pm SD	CV (%)
Judo ($n = 21$)		
SJFT _{TT} (throws)	27.8 \pm 2.2	8.0
SJFT _{INDEX}	10.9 \pm 1.0	9.0
Sprint running ($n = 13$)		
Sprint _{20m} (s)	2.17 \pm 0.0	3.0
200-m time trial (s)	23.4 \pm 0.8	3.0
Futsal ($n = 18$)		
RSL _{BT} (s)	4.16 \pm 0.2	4.0
RSL _{MT} (s)	3.98 \pm 0.1	5.0
RSS _{BT} (s)	5.50 \pm 0.2	4.0
RSS _{MT} (s)	5.32 \pm 0.2	4.0

SD – standard deviation, CV – coefficient of variation, SJFT_{TT} – Special Judo Fitness Test total throws, SJFT_{INDEX} – index of SJFT, RSL – repeated straight line sprint, RSS – repeated shuttle sprint, BT – best time, MT – mean time

lack of correlation between the absolute residuals and lnBM suggests homoscedasticity for residuals. Moreover, the high coefficient of determination (R^2) and the absence of relationship between scaled variables and body mass suggest that the allometric model is appropriated for removing the body mass effect of practically all variables, except for SJ_{MPO} in judokas. In this case, the ratio standard was assumed once the body mass effect was removed and confirmed by Tanner's exceptional circumstance, in which the ratio between the CV of BM and SJ_{MPO} was practically equal to the correlation between these variables (Table 2).

After the confirmation of validity of the allometric modelling, the power output was scaled for body mass by using the specific allometric exponent for each variable. Table 3 presents the descriptive data of raw and scaled power, in addition to JH.

Table 4 shows that most vertical jump parameters (both in CMJ and SJ) presented significant and moderate to very large correlations with physical performance in judo, sprint running, and futsal. The correlations of power output variables (mean and peak values) with physical performance increased after scaling for body mass, mainly evidenced for judo and futsal. The scaled PPO and MPO, as well as JH seem to correlate in a similar magnitude with most physical performance variables, for all sports. When confronting the magnitude of these correlations between CMJ and SJ, except for SJFT_{INDEX}, large and very large correlations can be verified for CMJ while only moderate to large correlations for SJ.

Table 2. Log-linear regression and regression diagnoses for allometric modelling of power output

Test	CV_{BM}/CV_{VAR}	$r1$	TEC	R^2	b	RD	RH	$r2$
Judo								
CMJ _{PPO}	0.65	0.86	No	0.75*	1.3	0.44	< 0.01	0.04
CMJ _{MPO}	0.61	0.83	No	0.70*	1.3	0.98	< 0.01	0.03
SJ _{PPO}	0.74	0.83	No	0.68*	1.11	0.29	< 0.01	0.02
SJ _{MPO}	0.72	0.73	Yes	–	1	–	–	–
Sprint running								
CMJ _{PPO}	0.51	0.74	No	0.50*	1.41	0.37	< 0.01	< 0.01
CMJ _{MPO}	0.48	0.67	No	0.41*	1.29	0.48	< 0.01	0.01
SJ _{PPO}	0.49	0.78	No	0.58*	1.52	0.81	< 0.01	< 0.01
SJ _{MPO}	0.46	0.74	No	0.50*	1.47	0.40	< 0.01	0.01
Futsal								
CMJ _{PPO}	0.85	0.68	No	0.57*	0.94	0.11	< 0.01	-0.07
CMJ _{MPO}	0.80	0.72	No	0.56*	1.04	0.74	< 0.01	-0.07
SJ _{PPO}	0.87	0.71	No	0.57*	0.88	0.32	< 0.01	-0.03
SJ _{MPO}	0.93	0.72	No	0.59*	0.84	0.27	< 0.01	-0.03

CV – coefficient of variation, BM – body mass, VAR – variable, $r1$ – relationship between variable and body mass, TEC – Tanner’s exceptional circumstance, R^2 – coefficient of determination of log-linear regression between variable and body mass, b – specific allometric exponent (slope of regression equation), RD – p value of residual distribution, both logarized by natural log, RH – residuals’ homoscedasticity, relationship between absolute residual and the lnBM, $r2$ – relationship between scaled variable and body mass, CMJ – countermovement jump, SJ – squat jump, PPO – peak power output, MPO – mean power output

* $p < 0.05$

Table 3. Descriptive statistics (mean, SD, and CV) of vertical jump performance variables in different sports

Variable	Judo		Sprint running		Futsal	
	Mean ± SD	CV (%)	Mean ± SD	CV (%)	Mean ± SD	CV (%)
CMJ						
JH (cm)	43.8 ± 5.5	12.0	52.8 ± 6.2	12.0	45.3 ± 5.9	13.0
PPO (W)	3443.2 ± 870.7	25.0	4052.6 ± 638.2	11.0	3172.9 ± 512.7	16.0
PPO (W · kg ^{-b})	13.3 ± 1.5	11.0	10.4 ± 1.1	11.0	66.0 ± 8.0	12.0
MPO (W)	1899.0 ± 506.1	26.0	2312.2 ± 377.9	16.0	1806.3 ± 310.8	17.0
MPO (W · kg ^{-b})	7.3 ± 0.9	13.0	9.6 ± 1.2	13.0	24.8 ± 3.16	13.0
SJ						
JH (cm)	41.5 ± 5.18	12.0	49.5 ± 5.7	12.0	39.9 ± 4.6	12.0
PPO (W)	3406.8 ± 757.3	22.0	4167.6 ± 676.2	16.0	3140.9 ± 497.7	16.0
PPO (W · kg ^{-b})	29.7 ± 3.4	11.0	6.7 ± 0.7	10.0	83.2 ± 9.16	11.0
MPO (W)	1545.1 ± 348.7	22.0	1888.6 ± 311.9	17.0	1357.8 ± 201.6	15.0
MPO (W · kg ^{-b})	17.2 ± 2.4	13.0	3.73 ± 0.4	12.0	42.4 ± 4.2	10.0

SD – standard deviation, CV – coefficient of variation, CMJ – countermovement jump, SJ – squat jump, JH – jump height, PPO – peak power output, MPO – mean power output, b – specific allometric exponent (see Table 2)

Table 4. Pearson's correlations between vertical jump parameters and physical performance tasks in sprint runners, judokas, and futsal players

Variable	Judo		Sprint running		Futsal			
	SJFT _{TT}	SJFT _{INDEX}	20 m	200 m	RSL _{BT}	RSL _{MT}	RSS _{BT}	RSS _{MT}
CMJ								
JH (cm)	0.68**	-0.41	-0.78**	-0.63*	-0.84**	-0.87**	-0.76*	-0.73*
PPO (W)	0.48**	-0.06	-0.75**	-0.65*	-0.39	-0.40	-0.03	-0.03
PPO (W · kg ^{-b})	0.63**	-0.44*	-0.70*	-0.69**	-0.79*	-0.81**	-0.62*	-0.58*
MPO (W)	0.48*	-0.14	-0.81**	-0.78**	-0.45	-0.47	-0.12	-0.11
MPO (W · kg ^{-b})	0.63**	-0.57*	-0.76**	-0.84**	-0.80*	-0.83**	-0.71*	-0.66*
SJ								
JH (cm)	0.64**	-0.39	-0.56*	-0.65*	-0.47*	-0.57*	-0.62*	-0.64*
PPO (W)	0.47*	-0.08	-0.62*	-0.69**	-0.28	-0.33	-0.07	-0.04
PPO (W · kg ^{-b})	0.58**	-0.46*	-0.64*	-0.55*	-0.49*	-0.63*	-0.56*	-0.49
MPO (W)	0.49*	-0.20	-0.43	-0.64*	-0.18	-0.20	0.03	0.04
MPO (W · kg ^{-b})	0.64**	-0.52*	-0.58	-0.53	-0.47	-0.53	-0.44	-0.40

SJFT_{TT} – Special Judo Fitness Test total throws, SJFT_{INDEX} – index of SJFT, RSL – repeated straight line sprint, RSS – repeated shuttle sprint, BT – best time, MT – mean time, CMJ – countermovement jump, SJ – squat jump, JH – jump height, PPO – peak power output, MPO – mean power output, *b* – specific allometric exponent (see Table 2)

* $p < 0.05$

** $p < 0.01$

Discussion

The main findings of this investigation were the following: (a) JH and scaled PPO and MPO presented a similar level of correlation with physical performance tests, for all sports analysed; (2) for most power output variables, it was necessary to use the allometric scaling method for removing the body mass effect. After scaling, PPO and MPO increased the relationship with specific physical performance as compared with the raw values; this was mainly evidenced for judo and futsal.

The vertical jump test has been widely used by researchers and practitioners to monitor fatigue [5, 25] and the chronic effects [7] of training, as well as to predict performance in several sports [26–28]. We conducted this study because there is a recurrent discussion in the literature in an attempt to determine the most appropriate parameter obtained from vertical jump (JH or power output) to represent lower limb performance. In addition, there was no conclusive evidence showing the capacity of these markers to replicate the athlete's event/competition. In this perspective, we evaluated the correlation between vertical jump and the physical performance of athletes from different sports in which lower limb muscle power is a determinant factor, such as judo [29, 30], futsal [31], and sprint running [26, 32]. In the vertical jump assessment, mechanical power output is considered to be the most direct indicator of lower limb muscle power

capability [12, 14]; however, the question concerning the usefulness of PPO or MPO has not been solved heretofore. Although both indexes represent the rate of mechanical work, the peak or instantaneous power obtained during the vertical jump corresponds to a specific moment close to the take-off, while MPO represents the entire push-off phase [16]. On the basis of our results, we can state that, in most cases, both MPO and PPO parameters (when properly adjusted for body mass) may be used similarly to represent physical performance in the sports investigated in the present study.

As revealed by our results, JH is correlated with physical performance tests in a similar magnitude of power output adjusted for body mass, for most analysed situations. Owing to its usability, JH is probably the most applied index in vertical jump assessment, but some studies have criticized it for not being able to represent lower limb mechanical power capability [11, 14, 18]. Although JH cannot be considered a power output marker indicator, it is a reliable variable with a moderate to strong correlation with adjusted lower limb mechanical power [18]. Therefore, we believe it may also be a practical option to monitor training for those who do not have a force platform to measure mechanical power.

With regard to the use of scaling for vertical jump assessment, it was verified that body mass affected the relationship of MPO and PPO with specific physical performance, especially for judo athletes and futsal

players. In this sense, we removed the effect of body mass for power output variables using an allometric approach, in which a specific allometric exponent was established for each variable. The criteria of Batterham and George [23] for the analysis of log-linear regressions were followed; thus, all allometric exponents have excellent adjustments. Nevertheless, for sprint runners, the relationship between specific performance (20-m and 200-m run) and power output seems not to be affected by body mass; i.e., the Pearson's r for raw values and scaled values of MPO and PPO is very close. This probably occurs because of the higher allometric exponent (b) obtained for runners, suggesting that each kilogram of a runner's body mass is more efficient in producing mechanical power than each kilogram of body mass for judokas and futsal players. Thus, for sprint runners, the scaling process may be unnecessary for this purpose.

When considering the different vertical jumps (CMJ and SJ) analysed in the present study, in general, higher correlations between CMJ variables and physical performance were observed. Probably, the specificity of muscular contraction involved in CMJ may explain the results. This muscle function is the stretch-shortening cycle, where the preactivated muscle is first stretched (eccentric action) and then the shortening (concentric action) occurs, allowing the use of elastic energy. The stretch-shortening cycle may be observed in basic locomotion or sports movements like running, jumping, and throwing [33, 34].

Finally, some limitations may be addressed in the present study, as the limited number of sports and small sample size in each sport. As strengths, we can highlight that our findings reinforce the importance of not neglecting the allometric scaling method when the goal is to compare or correlate the physical performance between individuals with different body sizes, especially in team sports (e.g. futsal) and combat sports (e.g. judo); it is less important in sprint runners.

Conclusions

In summary, JH and power output seem to correlate in a similar magnitude with physical performance tests for most variables and sports analysed (judo, futsal, and sprint running). If power output (peak or mean) is used to monitor training, it is necessary to use a specific allometric adjustment for better interpretation of data, mainly for judokas and futsal players. From a practical point of view, we suggest that researchers and coaches may use JH as an index that represents

athletes' physical performance and allows for monitoring training effects.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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