Original Article

A novel index to classify vertical jump performance of athletes according to the body mass

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ABSTRACT

Purpose: this study aimed to present a novel index to classify athletes using jump height (JH) as an indicator of lower limb performance considering different levels of body mass (BM). Methods: Three hundred fourteen male athletes volunteered to participate of this study. The athletes were evaluated performing the countermovement jump. Sigmoid functions were used to estimate the JH median according to the athlete's BM and peak power output (PPO). The Jump Sigma Index was proposed, dividing the measured JH by predicted JH for BM or PPO. This index is a percentage metric that allows one to classify the athletes' JH in four levels (Superior, Median-Superior, Median-Inferior, Inferior). Sigmoid functions ($r^2 = .99$; $p < .01$) were used as an explanatory model for the relationship of JH medians with BM (SigmaBM) and PPO (SigmaPPO) medians for each BM interval. Results: The applicability of the method was verified by the high correlations observed between SigmaBM and SigmaPPO ($r = .985$, $p < .01$). The total error of the classification model in the four levels was only 7.9% when comparing the classifications from SigmaBM and SigmaPPO (Kappa = .88; $p < .01$), indicating almost perfect agreement. Conclusion: The Jump Sigma Index (SigmaBM) is a valid and practical index for classifying athletes using only JH and BM as indicators of lower limb performance.

Keywords: Sports performance; Muscle power; Countermovement jump; Biomechanics.

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INTRODUCTION

During a vertical jump, athletes produce high amounts of mechanical work over a short duration to displace their body mass. Thus, this movement became the most frequently and routinely used test by coaches and researchers for evaluating the lower limb power output of athletes (Cormie, McGuigan, and Newton, 2011; Cronin and Sleivert, 2005). The maximum power output obtained in a vertical jump has been considered the most representative variable related to the athletic performance in several sports modalities (Nedeljkovic, Mirkov, Bozic, and Jaric, 2009; Pazin, Berjan, Nedeljkovic, Markovic, and Jaric, 2012). The mechanical power can be directly calculated from the ground vertical reaction force using a force platform (Harman, Rosenstein, Frykman, Rosenstein, and Kraemer, 1991). But the use of this equipment generally is restricted to large sports training centres or university laboratories, especially due to their high cost and difficulty in transportation.

Alternatively, some studies have suggested using jump height (JH) as a power output indicator per se (Markovic and Jaric, 2005; Markovic and Jaric, 2007; Young, Cormack, and Crichton, 2011). The main advantage of using JH is the lower cost of equipment for this purpose (e.g., contact mat) and greater practicality to evaluate the performance of lower limbs. However, the literature has shown that only approximately 45% of peak power output (PPO) variance is explained by JH (Aragón-Vargas and Gross, 1997; McBride, Kirby, Haines, and Skinner, 2010), suggesting that evaluation of lower limb performance using JH might not be a representative measure of PPO. On the other hand, it has been suggested that JH associated to body mass (BM) can be used to estimate the PPO from different regression equations (Amonette et al., 2012; Harman et al., 1991; Quagliarella, Sasanelli, Belgiovine, Moretti, and Moretti, 2011). These prediction equations present good to excellent coefficients of determination (Tessier, Basset, Simoneau, and Teasdale, 2013); therefore, they are apparently reliable, at least when analysing the average values of large groups.

It is known that PPO estimation from BM and JH also has some limitations, for example, the lack of a theoretical rationale explaining the link of PPO with BM and JH. Thus, it is uncertain whether all athletes with the same BM and JH produce the same power output (Samozino, Morin, Hintzy, and Belli, 2008). In addition, as presented in a recent article (Ache-Dias, Dal Pupo, Gheller, Kulkamp, and Moro, 2016), the prediction method fails in the individual context. According to this study, the classification of individuals into three distinct categories of PPO (superior, intermediate, and inferior) differs when comparing the actual values (measured in force platform) to the values estimated by equations. This happens because, although prediction equations present a low average error (bias), the random error is too large (± 600 w in some regression models), similar to found by Tessier et al. (2013). This high variability of the prediction's method limits the interindividual comparisons, and it does not provide reliable data for an adequate individual monitoring of PPO and the training load control over a season. So, the usage of vertical jump height as a measure of lower limb performance has been very discussed and criticized for not being able to represent the lower limbs' mechanical power capabilities (Knudson, 2009; Kons, Ache-Dias, Detanico, Barth, and Dal Pupo, 2018; Morin, Jiménez-Reyes, Brughelli, and Samozino, 2019).

In summary, the traditional model using JH, PPO, and BM is unable to precisely estimating PPO, and it does not allow using vertical jump height as a good indicator of power output. Therefore, the use of vertical jump for lower limb performance assessment without force platforms can be a challenging task. As an alternative, we present a new approach to the triad JH-PPO-BM. Instead of using the relationship between BM and JH to estimate PPO (traditional model), we invert the direction of the arrow of analysis and present an index based on the JH estimated by BM and PPO independently. The JH predicted by PPO will be used to validate the JH estimated by BM, assuming the premise of existence of a linear relationship between PPO and BM when considering central tendency values.

Therefore, the objective of this study was to present a novel index to classify athletes using JH as an indicator of lower limb performance considering different levels of BM. Considering the traditional premise of linear relationship between BM and PPO (Ache-Dias et al., 2016; Carlock et al., 2004), we hypothesized that the relations between JH and PPO and between JH and BM are very similar. This allowed us to present a unique mathematical model to estimate the JH according to the athletes' BM and PPO. From this, an index to classify athletes' performance was proposed using only BM and JH, very similar of using the actual PPO measured in a force plate, at least in respect to jump height median expected.

MATERIALS AND METHODS

Participants

Three hundred fourteen male athletes (age = 24.78 ± 5.1 years; BM = 73.83 ± 8.94 kg; height = 1.78 ± 0.08 m; and Body Mass Index = 23.37 ± 2.03 kg/m^2) from different sports (futsal, judo, volleyball, tennis, taekwondo, soccer, basketball, hockey, sprinting, and middle-distance running) volunteered to participate of this study. Participants had a minimum of three years of experience in their sporting modality, training at least three days a week. The athletes were competing at the state or national level. Participants reported no injuries or other preconditions that impeded their maximal physical performance. All received a detailed explanation of the purpose and methods of the study before signing a written informed consent form. The study was approved by the local University Ethics Committee according to the Declaration of Helsinki.

Measures and Procedures

The athletes were evaluated performing the countermovement jump (CMJ). Before CMJ assessment, the participants performed a brief familiarization/warm-up involving 1 minute of hopping on a trampoline, 2 series of 10 hops on the ground, and 8–10 submaximal CMJ. For CMJ evaluation, participants were instructed to start from a static standing position and to perform a countermovement (descent phase) followed by a rapid and vigorous extension of the lower limb joints (ascent phase), jumping as high as possible. Participants were asked to sustain their trunk as vertically as possible, whereas their hands remained on their hips (akimbo). The vertical jumps were performed on a piezoelectric force platform (9290AD, Kistler, Quattro Jump, Winterthur, Switzerland). Each participant performed three jumps with a rest interval of 1 minute in between. Jump height was obtained by double integration of ground reaction force (GRF). Power output was calculated by multiplying GRF by velocity in the ascent phase of the jump (from when the centre of mass velocity becomes positive until take-off) (Ache-Dias et al., 2016). The highest value of the curve (peak power output) was used for analysis.

Data analysis

When analysing large amounts of jumping data, the linearity between PPO and BM is not always clearly observed, probably because the performance spreads below and above a theoretical central tendency. Thus, the median of each variable of the triad (JH, PPO, and BM) was calculated over five BM intervals (see Table 1), allowing that the linearity of the relationship between BM and PPO should be manifested. From this, it was possible to analyse the relationships between JH and PPO and between JH and BM.

Table 1. Medians of body mass (BM), jump height (JH) and peak power output (PPO) according to each BM interval.

Percentile	N	BM (kg)	BM Interval (kg)	JH (cm)	JH Interval (cm)	PPO (w)	PPO Interval (w)
8	51	60.99	57-63.9	43.70	33.60-56.90	3076.15	2275.42-4618.25
24	50	67.29	64-68.9	44.25	38.60-54.50	3458.52	2837.71-4349.15
43	73	72.69	69-74.9	45.50	39.10-66.30	3734.60	3089.30-4941.64
73	108	78.41	75-84.9	46.60	34.30-61.10	3967.12	3028.20-5278.67
95	32	88.90	85-99.0	47.25	34.20-64.50	4678.95	3196.46-5858.05

Considering the large number of participants in the BM intervals between 69 kg and 84.9 kg in relation to the other groups, we performed a further analysis (random exclusion) to reduce the number of athletes of these groups. Thus, 51 athletes remained in the group at the end of the process. The group with a higher BM median (85 to 99 kg) remained with 32 members in this analysis, given the greater difficulty of recruiting high-performance athletes with this BM magnitude.

The data analysis allows us to use a unique mathematical model to estimate the JH median expected according to the athletes' BM and PPO. Then, we proposed a metric called Jump Sigma Index (alluding to the adopted sigmoid dose-response mathematical model) by dividing measured JH by predicted JH for BM (SigmaBM) or PPO (SigmaPPO). The sigmoid regression models are presented in the results section (equations 3 and 4). Dividing actual and predicted JH provided by both equations, it was possible to verify the similarity between these proportions when using BM as well as when using PPO as a predictor variable. This allowed us to assume that it is possible to use this approach as an index to classify athletes' lower limb performance using only BM and JH, which is very similar to using the actual PPO measured in a force plate with respect to expected JH median.

To make the index more visually explanatory, the value of the ratio was decreased by 1 and multiplied by 100 so that any value above, below, or equal to zero would represent its proximity in percent units to the expected median (equations 1 and 2).

$$Sigma_{BM} = \left(\left(\frac{JH(cm)}{JH\ predicted\ for\ BM\ (cm)}\right) - 1\right) * 100 \qquad \text{Equation 1}$$

$$Sigma_{PPO} = \left(\left(\frac{JH(cm)}{JH\ predicted\ for\ PPO\ (cm)}\right) - 1\right) * 100 \qquad \text{Equation 2}$$

A four-level classification scale based on the SigmaBM (%) of each athlete, was elaborated as follows: SigmaBM > 15 (Superior); 0 < SigmaBM ≤ 15 (Median-superior); 0 > SigmaBM ≥ -15 (Median-inferior); and SigmaBM < -15 (Inferior). In this classification model, the zero of the scale was interpreted as referring to performance identical to the expected median for each specific BM range. Thus, performance levels can be used for an overall ranking, while SigmaBM can be useful for individual comparisons within each of the four levels of performance.

The normal distribution of BM, JH, PPO, SigmaBM, and SigmaPP was not observed in the Shapiro-Wilk test ($p < .05$), probably due to the existence of discrepant values. The option of maintaining extreme values rather than excluding them from analysis was adopted by the understanding that discrepant values represent individuals with performance well above or well below the average, which might be useful to determine the extreme limits of the performance spectrum that can be observed in practice. Thus, for the central tendency to be less affected by extreme values, the median of the data was used as a measure of central tendency.

The adequacy of the mathematical modelling approach was verified based on the magnitude and significance of the determination coefficient of the regressions for estimation of JH using BM and PPO as well as for the magnitude and significance of the correlation between actual and expected median values according to BM and PPO over the five BM intervals. To verify the level of similarity between the SigmaBM and SigmaPPO, a non-parametric test to compare the medians and Spearman's correlation were used. In addition, a logarithmic transformation of the SigmaBM and SigmaPPO values was performed as a statistical artifice for normalizing the data, allowing the use of parametric tests (t-test and Pearson's correlation). The intra-class Kappa correlation index and the intra-class correlation coefficient (ICC, two-way mixed effect model) were used to verify the consistency of homogeneity between SigmaBM and SigmaPPO. The following Kappa classification was adopted: zero indicates no agreement, 0 – .20 slight, .21 – .40 fair, .41 – .60 moderate, .61 – .80 substantial, and .81 – 1 almost perfect agreement (Landis and Koch, 1977). For ICC classification, values less than .5 indicate poor reliability, values between .5 and .75 indicate moderate reliability, values between .75 and .9 indicate good reliability, and values greater than .90 indicate excellent reliability (Koo and Li, 2016).

RESULTS

The linearity of the relationship between BM and PPO was confirmed for the median of the specific BM intervals (r = 1; p < .01), allowing further analyses.

A sigmoid function (dose-response model) was used as an explanatory model for the relationship of JH medians with BM and PPO medians for each BM interval (see Figure 1). Considering the high coefficient of determination for the regressions, the sigmoid model presented a very representative adjustment of the relationships between the variables over the five BM intervals, and the actual and predicted values were likely the same.

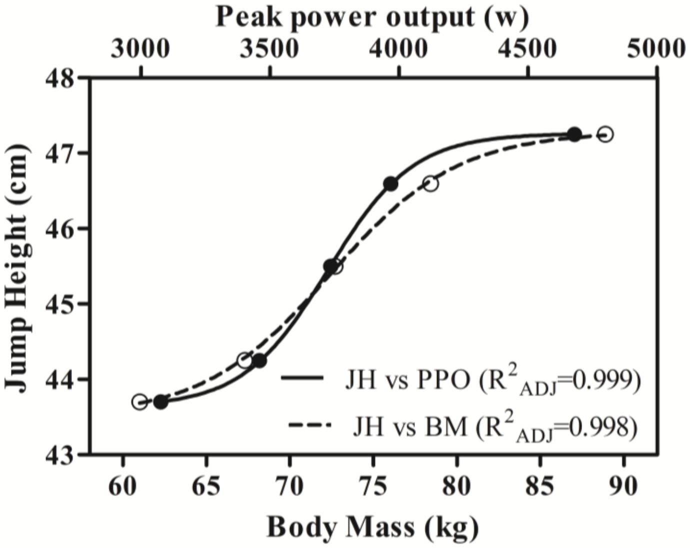

Figure 1. The sigmoid model representing the relationship of jump height (JH) vs. peak power output (PPO) and JH vs. body mass (BM).

Using the equations below, the median of expected JH was estimated using BM (Equation 3) and PPO (Equation 4) as predictive variables, respectively. Therefore, SigmaBM and SigmaPPO were calculated by replacing the denominator of equations 1 and 2 with the result obtained by equations 3 and 4.

$$JHexpected(cm) = 43.50196 + \frac{3.78439}{\left(1 + 10^{((72.422 - BM)\times 0.11354)}\right)} \qquad Equation\ 3$$

$$JHexpected(cm) = 43.63486 + \frac{3.6297}{\left(1 + 10^{((3723.535 - PPO)\times 0.00264)}\right)} \qquad Equation\ 4$$

The applicability of the method was verified by the high magnitude of the correlations observed between SigmaBM and SigmaPPO, both from non-parametric (rho = .98; p < .01) and parametric tests (r = .99, p < .01), as shown in Figure 2. The adequacy of the method was also confirmed after the equalization of the number of participants per BM interval, preserving the linearity of the relationship between BM and PPO (r = 1, p < .01) and the representative capacity of the sigmoid model (SigmaBM: r^2 = .97, SigmaPPO: r^2 = .98).

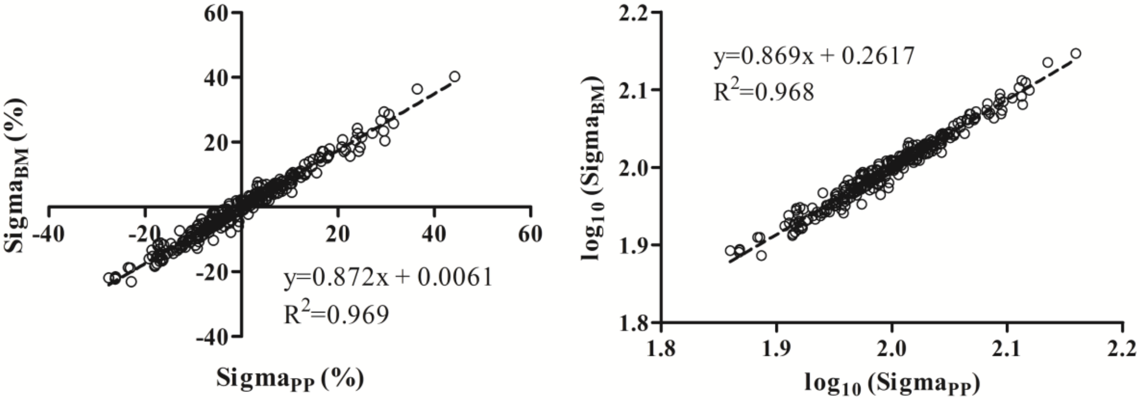

Figure 2. Relationship between SigmaBM and SigmaPP for raw (left panel) and log values (right panel).

The total error of the classification model in four levels was only 7.9 % when comparing the classifications from SigmaBM and SigmaPPO (Kappa = .88; p < .01), indicating almost perfect agreement. Thus, only 25 of 314 athletes were classified differently when comparing the indices (ICC = .98; ICC = .99; p < .01; single and average measures, respectively). In Figure 3, the performance of the athletes in four performance categories can be visualized collectively as well as individually within each category. Thus, the BM effect is removed and the performance classifying element is the magnitude of SigmaBM. This dispersion diagram allows us to compare the performance of any individual to the performance presented by the set of athletes evaluated in this study.

To better understanding of the method, Table 2 shows SigmaBM and SigmaPPO of representative individuals for each BM interval as well as the magnitude of the observed correlation between SigmaBM and SigmaPPO for each of these intervals (when all athletes are compared).

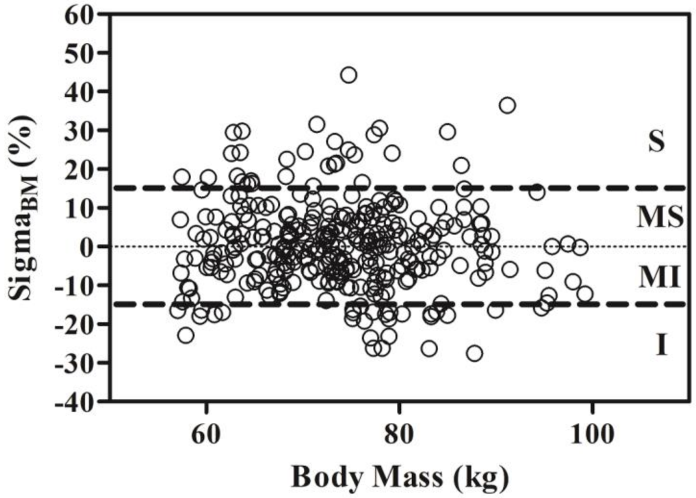

Figure 3. Classification method in four levels of performance according to SigmaBM. S = superior; MS = median-superior; MI = median-inferior; I = inferior.

Table 2. Application of method for representative individuals of each BM interval.

Athletes	BM interval (Kg)	BM (kg)	JH (cm)	PPO (w)	Sigma$_{BM}$ (%)	Sigma$_{PPO}$ (%)	Classification	r
A	57-63.9	63.22	51.80	3307.68	18.22	17.99	Superior	.99
B		62.65	46.60	3031.01	6.45	6.67	Med-sup	
C		61.48	40.90	2815.79	-6.42	-6.30	Med-inf	
D		57.05	36.40	2509.06	-16.45	-16.58	Inferior	
F	64-68.9	64.71	51.1	3504.04	16.28	15.11	Superior	.97
G		65.74	45.2	3440.86	2.58	2.29	Med-sup	
H		65.3	42.6	3113.83	-3.21	-2.56	Med-inf	
I		67.61	39.0	2860.12	-12.04	-10.66	Med-inf	
K	69-74.9	73.28	55.3	4484.73	21.25	17.088	Superior	.98
L		70	46.4	3696.61	3.54	2.42	Med-sup	
M		70.2	43.6	3353.53	-2.81	-0.86	Med-inf	
N		72.69	41.4	3089.30	-8.93	-5.28	Med-inf	
P	75-84.9	77.38	59.9	4896.01	28.89	26.74	Superior	.99
Q		75.8	49.2	3960.09	6.54	5.65	Med-sup	
R		77.73	43.1	3820.53	-7.37	-6.24	Med-inf	
S		76.39	37.4	3535.92	-19.21	-15.98	Inferior	
P	85-99	91.19	64.5	5858.04	36.48	36.46	Superior	.99
Q		88.36	50.0	4268.03	5.88	6.07	Med-sup	
R		88.18	43.4	4036.45	-8.10	-7.25	Med-inf	
S		87.78	34.2	3196.46	-27.57	-21.87	Inferior	

Note: BM, body mass; JH, measured jump height; PPO, peak power output; r, Pearson's correlation between SigmaBM and SigmaPP for each of these intervals (when all athletes are compared).

DISCUSSION

The current study presents a new approach of the triad jump height - peak power output - body mass for classifying the performance of lower limbs using the Jump Sigma Index. According to the results, the main hypothesis of the study (linearity of the relationship between BM and PPO for the median of the specific BM intervals) was confirmed, allowing calculation of the Sigma Index. The SigmaBM represents the percentage metric distance of the actual JH in relation to the expected JH median according to the athlete's BM (estimated by a sigmoid mathematical model). We used a similar index that uses athletes' PPO (SigmaPPO) to estimate expected JH median as a reference to "validate" the SigmaBM. According to our knowledge, this is the first study to propose an inversion in the arrow of the triad analysis in which JH is predicted instead of PPO, allowing a more practical assessment of lower limb performance.

The assessment of the lower limb power output of athletes is a permanent interest of coaches and sports scientists due to the great importance of this physical component for performance in many sports modalities (Ache-Dias et al., 2016; Kons et al., 2018). In the last three decades, researchers have been trying to understand the relationship between vertical jump, muscle power, and body mass, aiming to use the JH as a muscle power indicator (Nedeljkovic et al., 2009; Pazin et al., 2012). However, JH (when used independently) has been considered a poor indicator of lower limb muscle power (Kons et al., 2012; Morin et al., 2019). Likewise, the prediction models to estimate PPO based on a linear relationship with BM and JH fail when applied in the individual context (due to large random error) (Ache-Dias et al., 2016).

According to Morin et al. (2019), some aspects such as individual push-off distance, optimal loading, and force-velocity profile might explain why JH and PPO are not fully related. In this way, Samozino et al. (2008) suggested using an equation based on fundamental laws of mechanics for estimating lower limb mechanical power using BM, JH, and the push-off distance. However, only the mean power output can be estimated from Samozino's equation. Some studies have shown that PPO would be the most appropriate descriptor of lower limb muscle power capabilities correlated with athletic (Carlock et al., 2004; Hayes et al., 2013; Lamberts, Lambert, Swart, and Noakes, 2012; West, Owen, Cunningham, Cook, and Kilduff, 2011) and functional (Puthoff and Nielsen, 2007) performance. Nevertheless, there is no consensus about the most adequate variable to represent the lower limb performance.

In the current study, we present another perspective in using JH for lower limb performance assessment, the Jump Sigma Index. The high correlation observed between SigmaBM and SigmaPPO (Figure 2) suggests that it is possible and practical to classify athletes using only BM and JH values, which is similar to using PPO and JH. As observed in Figure 1, a nonlinear relationship between JH and PPO as well as between JH and BM was observed instead of the linearity supposed by the classical approach of the triad JH-PPO-BM. The sigmoid dose-response model indicates that lighter and heavier athletes pay a more expensive conversion tax (PPO/JH) compared to athletes with intermediate levels of BM (~66-79 kg). Thus, for these individuals, more units of BM (kg) and consequently of PPO (w) are necessary to increase each cm of JH. It is important to highlight that our data do not allow for investigating why lighter and heavier athletes are less able to convert jump height to PPO or vice-versa.

From a biological point of view, our approach starts from the existence of an intrinsic linear relationship between BM and PPO. This argument is necessarily assumed when power output is divided by BM to assure normalized data (a common practice on research and field). However, when analysing large amounts of jumping data, this linearity is not always clearly perceived, considering the level of statistical correlation between PPO and BM (r ~ .7) (Kons et al., 2018). We believe it happens because the performance spreads below and above the mentioned theoretical central tendency straight line, which disturbs any prediction model when considering absolute values. This dispersion probably occurs because BM is not an exclusive variable for generating mechanical power, in which anthropometric characteristics, movement technique, and neuromuscular properties are key factors to produce high amounts of power output during vertical jumping (Jiménez-Reyes et al. 2014).

The great practicality of the Jump Sigma Index for assessing lower limb performance is that only a single jump is necessary. However, Morin and co-workers stated that it is inappropriate to assure maximum power output in a single jump assessment, because maximal output is achieved only in an optimal loading condition (Morin et al., 2019). Although it is reasonable to apply a multiple load protocol when evaluating PPO, it is important to highlight that our approach does not intend to estimate PPO. As an alternative, we are presenting a comparative scaling for unloaded single jump performance. Although athlete's power output might not reach the maximal possible values (PPO) in a single jump, as evidenced by Morin et al. (2019), the highest jump height is achieved with no extra load (independent of the power achieved). Thus, a load-profile is not necessary when applying our approach.

From the practical point of view, the Jump Sigma Index allows the use of jump height and body mass as indicators of lower limb performance during vertical jump without the use of a force plate. From this index, athletes will know if their jump height is adequate for their BM, allowing a general classification of vertical jump performance. It is important to highlight that the Sigma Index may be calculated even when a contact mat or infrared sensors are used, thus increasing the practicality of the method. Meanwhile, the jump height obtained from flight time methods underestimate (~10 cm) the jump height when compared to the values obtained from a force plate; thus, it is necessary to correct the jump height values, as suggested by Dias et al. (2011). We are making available a spreadsheet (https://figshare.com/s/de57c732c42fa48bdd9f), which allows direct access to the calculation of Sigma Index and the general classification into different sports modalities.

Lastly, we can highlight as a limitation of the present study that the Sigma Index can be used only for male athletes with BM ranging from 57 to 99 kg, and it can be applied only in countermovement jump assessment.

CONCLUSION

A novel approach of the triad vertical jump – peak power output – body mass was established for classifying the performance of lower limbs using the Jump Sigma Index. The high correlation observed between SigmaBM and SigmaPPO suggests that it is possible and practical to classify athletes using body mass and jump height, which is similar to using peak power output and jump height. This is the first study providing evidence of using jump height for lower limb assessment considering the body mass as an alternative to the traditional model in which jump height is considered a lower limb power indicator per se.

AUTHOR CONTRIBUTIONS

Conceived and designed the experiments: Külkamp W, Dal Pupo J, Ache-Dias J; Performed the experiments: Külkamp W, Dal Pupo J, Ache-Dias J; Analysed the data: Külkamp W, Ache-Dias J; Contributed reagents/materials/analysis tools: Külkamp W, Dal Pupo J, Ache-Dias J; Wrote the paper: Külkamp W, Dal Pupo J, Ache-Dias J.

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DISCLOSURE STATEMENT

The authors declare no conflicts of interest.

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