

A few additional reasons why vertical jump height should not be used to predict leg power

Luis F. Aragón-Vargas y María I. González-Lutz

Abstract

Jump height continues to be widely used to predict power in humans. Individual progress is often monitored on the basis of estimated power, but prediction equations are based on group data. **Objectives:** to show that vertical jump performance (VJP) and mechanical power are poorly associated, particularly within individuals. **Design:** regression analysis. **Methods:** Two experiments are presented. First, 52 physically active male college students performed five maximal vertical jumps each. Second, three young male participants performed 50 maximal jumps each. Participants rested for 1 minute between jumps. VJP was calculated from kinematic data as peak body center of mass (BCOM) minus standing BCOM; peak power (PEAKPWR) was calculated from the vertical ground reaction force registered by a force plate, and average power (MEANPWR) during propulsion from the change in potential energy of BCOM. Regression analyses used standardized VJP scores as the predictor variable and standardized power scores as the resulting variables, expecting an identity function of $y = x$ (intercept = 0, slope = 1) and $R^2 = 1$. **Results:** In experiment 1, the model for $zPEAKPWR$ $R^2 = 0.9707$ ($p < 0.0001$) but slope (0.3452) $\neq 1$ ($p = 8.7 \times 10^{-15}$). The model for $zMEANPWR$ $R^2 = 0.9239$ ($p < 0.0001$); nevertheless, slope (0.4257) $\neq 1$ ($p = 1.15 \times 10^{-5}$). In experiment 2, all individual models for $zPEAKPWR$ and $zMEANPWR$ resulted in poor associations ($R^2 \leq 0.21$) and slopes $\neq 1$ ($p \leq 0.001$). **Conclusion:** Regression analysis for individuals, and even for groups, confirms that VJP is a poor predictor of mechanical power.

KEY WORDS: Kinematics, Biomechanical phenomena, Biomechanics, Sports, Lower limbs, Within-subject analysis.

Más razones para no usar la altura del salto vertical en la predicción de la potencia de piernas

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Resumen

La altura del salto se sigue usando ampliamente para predecir la potencia en seres humanos. El progreso individual a menudo se monitorea usando una estimación de la potencia, pero las ecuaciones de predicción se desarrollaron en datos grupales. **Objetivos:** demostrar que la altura del salto vertical (ASV) y la potencia mecánica tienen una pobre correlación, particularmente en un mismo individuo. **Diseño:** análisis de regresión. **Métodos:** se presentan dos experimentos. Primero, 52 estudiantes universitarios físicamente activos ejecutaron cinco saltos verticales máximos cada uno. Segundo, tres participantes masculinos ejecutaron 50 saltos máximos cada uno. Los participantes descansaron 1 minuto entre saltos. ASV se calculó a partir de los datos cinemáticos como posición más alta del centro de masa corporal (CDM) menos CDM de pie; la potencia pico (PEAKPWR) se calculó a partir de la fuerza vertical de reacción registrada por una plataforma de fuerza y la potencia promedio (MEANPWR) durante la propulsión a partir del cambio en la energía potencial del CDM. Los análisis de regresión utilizaron puntajes estandarizados de ASV como la variable predictora y puntajes estandarizados de potencia como las variables resultantes, con la expectativa de obtener una función de identidad $y = x$ (intercepto = 0, pendiente 0 1) y $R^2 = 1$. **Resultados:** En el experimento 1, el modelo para $zPEAKPWR$ arrojó $R^2 = 0.9707$ ($p < 0.0001$) pero la pendiente (0.3452) $\neq 1$ ($p = 8.7 \times 10^{-15}$). El modelo para $zMEANPWR$ dio $R^2 = 0.9239$ ($p < 0.0001$); sin embargo, la pendiente (0.4257) $\neq 1$ ($p = 1.15 \times 10^{-5}$). En el experimento 2, todos los modelos individuales para $zPEAKPWR$ y $zMEANPWR$ arrojaron asociaciones débiles ($R^2 \leq 0.21$) y pendientes $\neq 1$ ($p \leq 0.001$). **Conclusión:** El análisis de regresión para individuos y aún para grupos confirma que la ASV es un pobre predictor de la potencia mecánica.

PALABRAS CLAVES: Cinemática, Fenómenos biomecánicos, Biomecánica, Deporte, Tren inferior, Análisis intra-sujeto.

52 Introduction

53 Human power testing has fascinated exercise scientists for decades. Mechanical power is an important
54 factor in sports performance, but its measurement requires sophisticated and expensive equipment. The
55 gold-standard power test commonly used in the laboratory uses a cycle ergometer: the Wingate test (Bar-
56 Or, 1987), although better cycling power tests have been devised, particularly for peak power (Coso &
57 Mora-Rodríguez, 2006). Cycling tests are often criticized because they don't resemble sports involving
58 running or jumping; hence the desirability of measuring power during a vertical jump. Nevertheless, the
59 latter also requires expensive, sophisticated laboratory equipment, such as force platforms or motion capture
60 systems. Testing for vertical jump height or vertical jump performance (VJP), on the other hand, is practical,
61 reliable, and precise (Aragón-Vargas LF, 2000). Furthermore, VJP has been widely used to predict power
62 in humans (Harman et al., 1991; Kirkendall et al., n.d.; Morin et al., 2019; Samozino et al., 2008). Despite
63 the apparent logic of a strong association between mechanical power of the lower limbs and vertical jump
64 height, there are important limitations involved in the calculation and prediction of the former from the
65 latter.

66 Initial attempts incurred a basic mistake: using the flight time of the vertical jump in the mathematical
67 calculation of power. This has been called “the Lewis formula” and has been shown to calculate the power
68 of the falling jumper (Harman et al., 1991), a useless value (more on this common error below). The
69 association between VJP and mechanical power is not a simple mathematical function. Vertical jump height
70 depends mostly on the vertical take-off velocity of the body center of mass (BCOM), but also on the position
71 of BCOM at the instant of take-off (Aragón-Vargas LF & Gross MM, 1997a, 1997b). Even if researchers
72 focus on take-off velocity alone, this velocity is a function of the mechanical work performed during push-
73 off, not of the mechanical power. The measurement of that additional variable necessary for the calculation
74 of power, namely, time of propulsion or push-off, requires laboratory-grade equipment and cannot be
75 calculated from VJP.

76 Bosco and his colleagues (Bosco C et al., 1983) proposed a mathematical function intended to calculate
77 average mechanical power from a series of vertical jumps on a simpler timing device. This jumping

78 ergometer method is also widely used, but Herbert Hatze (Hatze, 1998) carefully showed that because of a
79 series of invalid assumptions used in deriving the formulae, together with an average error of about 5%
80 associated with a 4.48% standard deviation, this method cannot be considered reliable or valid for evaluating
81 serial rebound jumps.

82 An alternative strategy is to use regression equations; these are widely used in exercise science (Canavan
83 & Vescovi, 2004; Lara-Sánchez et al., 2011; Sayers et al., 1999), although their validity has been questioned.
84 A descriptive study (Tessier et al., 2013) showed that even for their own carefully developed equation ($r^2 =$
85 0.94) using highly trained athletes, the minimal difference in estimated power necessary to consider that
86 two individuals were different, was too large (689.3 W). They concluded that the height of the jump should
87 not be used to accurately predict the actual mechanical power of an individual. Most recently, Morin and
88 his colleagues (Morin et al., 2019) published a solid critique of the use of VJP in the prediction of mechanical
89 power, demonstrating that individual body mass, push-off distance, optimal loading, and the force-velocity
90 profile are important variables that confound the relationship between jump height and power; they
91 proceeded to propose a different testing method and calculations that look promising, but further evaluation
92 is necessary.

93 Meanwhile, better regression equations continue to be based on jump height as the main predictor; there
94 is a need for a stricter evaluation of the validity of using VJP for this purpose. In a conventional regression
95 approach, the strength of the association is evaluated for larger or smaller groups of participants. But even
96 if high coefficients of determination (R^2) were found, they would only show a group effect, not a within-
97 subject effect. In other words, most regression equations for mechanical power are based on group data,
98 however, their results are used to predict individual performance and monitor individual progress. The issue
99 was hinted at by Tessier (Tessier et al., 2013), who ran a preliminary analysis on four jumps by the same
100 participant but did not probe deeper into it. The key question is: how good is the association between vertical
101 jump performance and mechanical power at the individual level? This should be addressed by having a few
102 individuals perform multiple maximal vertical jumps.

103 Therefore, the purpose of the present study was to use two existing vertical jump databases to confirm
104 the validity of using vertical jump performance as a predictor of mechanical power for individuals and to
105 propose a new methodology for evaluating performance prediction models in exercise science.

106

107 Methods

108 This study used two datasets from previous experiments, originally designed to investigate the
109 kinesiological factors that distinguish good jumpers from poor jumpers (Aragón-Vargas LF & Gross MM,
110 1997a), and to understand what a jumper does differently from one jump to another resulting in different
111 jump heights, even when instructed to always jump as high as possible (Aragón-Vargas LF & Gross MM,
112 1997b). Informed consent was obtained for all participants, in accordance with the protocol approved on
113 September 21, 1993, by the Human Subjects Review Board, School of Education, The University of
114 Michigan. For experiment 1, 52 physically active male college students performed five maximal vertical
115 jumps each, starting from the position of their choice, with their hands on their hips. All jumps involved a
116 countermovement. Participants completed three practice jumps before data collection and were required to
117 wait for 1 min after each trial. They performed the jumps barefooted, wearing only a swimsuit or pair of
118 shorts.

119 For experiment 2, three young males performed 50 maximal jumps each on the force platform; they were
120 required to sit and rest for 1 minute after each jump. These were the worst, average, and best jumpers in a
121 larger study looking at VJP differences within individuals (Aragón-Vargas LF & Gross MM, 1997b).

122 Ground reaction forces and moments of force were collected with a Bertec force plate (Model 4060A),
123 sampled at 300 Hz. A video-based real-time, three-dimensional motion analysis system (Motion Analysis
124 Corp.) was used to collect and process kinematic data at 60 Hz; these data were filtered with a low-pass,
125 fourth-order Butterworth filter with an effective cutoff frequency of 8Hz. The biomechanical model used,
126 and all analytic procedures, have been described in detail elsewhere (Aragón-Vargas LF & Gross MM,
127 1997a). Briefly, the human body was modeled as a planar (2-D), rigid-body system comprising four
128 segments linked by frictionless, hinge joints.

129 Vertical Jump Performance (VJP) was calculated for each jump from the kinematic data (see Eq. 1),
130 using the 2-D model, where $BCOM_{peak}$ is the position of the body center of mass at the highest point during
131 the flight, and $BCOM_{standing}$ is the position of the body center of mass with the participants standing still:

132 Eq. 1
$$VJP = BCOM_{peak} - BCOM_{standing}$$

133 Mechanical Power was calculated for the same jumps from the vertical ground reaction force and from
134 the change in potential energy of the whole body. Mean power (MEANPWR) during propulsion was derived
135 from the change in potential energy of the whole body, according to Eq. 2, where m is the body mass for
136 each individual in Kg, $g = 9.81 \text{ m}\cdot\text{s}^{-2}$, $Z_{takeoff}BCOM$ is the vertical coordinate of the body center of mass at
137 the instant of takeoff, $Z_{low}BCOM$ is the vertical coordinate of BCOM at the lowest point during push-off,
138 and t_{prop} is the time of push-off in seconds (Aragón-Vargas LF & Gross MM, 1997a):

139 Eq. 2
$$\bar{W} = mg(z_{takeoff}BCOM - z_{low}BCOM)/t_{prop}$$

140 PEAKPWR was obtained from the instantaneous mechanical power of the whole body, calculated
141 according to Eq. 3, where F_z is the vertical ground reaction force and $\dot{z}BCOM$ is the vertical component of
142 the instantaneous velocity of the body center of mass (Aragón-Vargas LF & Gross MM, 1997a):

143 Eq. 3
$$\dot{W} = F_z \times \dot{z}BCOM$$

144 Experiment 1 involved a traditional approach with 52 participants and 5 trials each. Data were analyzed
145 using standardized (z) results. Each model included participants and trials as random effects. One model
146 was used to predict $zPEAKPWR$, and another model to predict $zMEANPWR$, using $zVJP$ as the major
147 predictor. According to the validation objective, an identity function of $y = x$ (intercept = 0, slope = 1) and
148 $R^2 = 1$ were expected.

149 An individualized approach with 3 participants and 50 trials each was used for experiment 2. A single
150 model was attempted first, including all three participants and their trials. Afterward, individual models
151 were fitted. Regression analyses used standardized VJP scores ($zVJP$) as the predictor variable and
152 standardized peak power ($zPEAKPWR$) or mean power ($zMEANPWR$) scores as the resulting variable,

153 expecting an identity function of $y = x$ (intercept = 0, slope = 1) and $R^2 = 1$. All regression models were
154 tested using JMP Pro v.15.1.0 (SAS Institute, Inc.).

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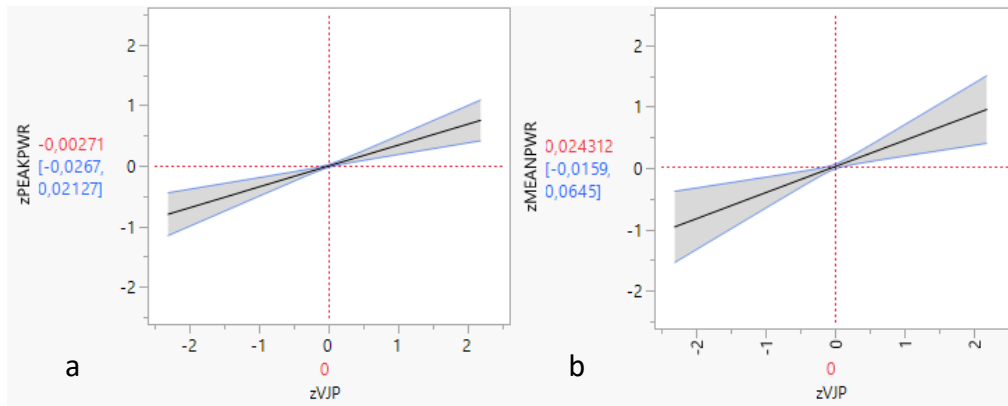
156 Results

157 For Experiment 1, the sample consisted of 52 males aged 20.2 ± 2.1 y.o. (mean \pm s.d.), height = $1.79 \pm$
158 0.06 m, and weight = 74.3 ± 8.6 kg. Vertical jump = 506 ± 70 mm (range: 372 to 663 mm). Peak power was
159 3863.2 ± 687.7 W. The three participants from experiment 2 were very similar in body weight: 70.9, 71.1,
160 and 65.5 kg for the worst, average, and best jumpers, respectively. They had a VJP (mean \pm s.d.) of 301 ± 9 ,
161 439 ± 17 , and 586 ± 14 mm, respectively; corresponding peak powers were 2079.3 ± 56.6 , 3706.0 ± 136.1 , and
162 4085.0 ± 74.2 W, respectively.

163 The first set of analyses corresponds to experiment 1. Figure 1a shows the adjusted line for zPEAKPWR
164 as predicted by zVJP, according to model $zPEAKPWR = k + s(zVJP) + \text{participant} + \text{trial} + \text{Error}$. The
165 association is strong: $R^2 = 0.9707$ ($p < 0.0001$) and the intercept (-0.0027) is not different from 0 ($p =$
166 0.8238). Nevertheless, the slope (0.3452) is significantly different from 1 ($p = 8.7 \times 10^{-15}$). Figure 1b shows
167 the adjusted line for zMEANPWR as predicted by zVJP, according to model $zMEANPWR = k + s(zVJP)$
168 $+ \text{participant} + \text{trial} + \text{Error}$. The association shows a strong $R^2 = 0.9239$ ($p < 0.0001$) and the intercept
169 (0.0243) is not different from 0 ($p = 0.2343$). Nevertheless, the slope (0.4257) is significantly different from
170 1 ($p = 1.15 \times 10^{-5}$).

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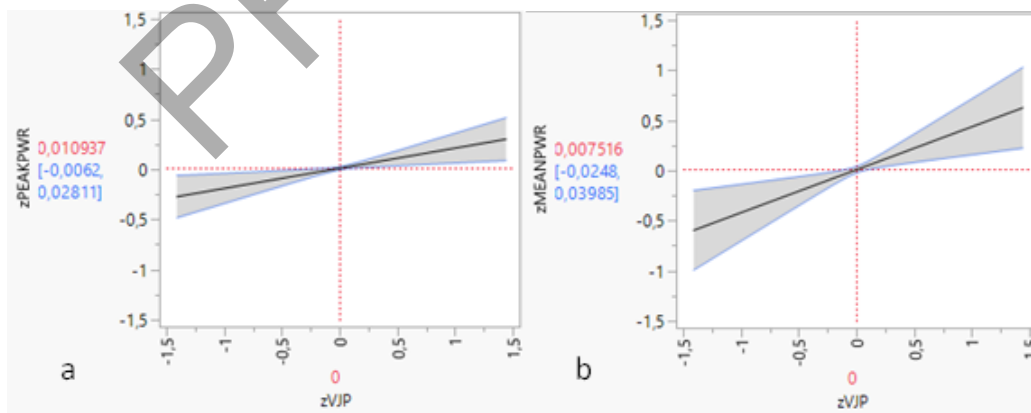
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173

174 **Figure 1.** Prediction of normalized power from normalized vertical jump performance. Experiment 1,
 175 between-subjects design, participants and trials as random effects. Participants = 52; trials = 5. (a): Peak
 176 mechanical power. Total valid data points = 256; $R^2 = 0.9707$; Intercept = -0.0027; Slope = 0.3452. (b):
 177 Mean mechanical power. Total valid data points = 252; $R^2 = 0.9239$; Intercept = 0.0243; Slope = 0.4257.
 178 Source: the authors. Figures were created using JMP Pro v.15.1.0 (SAS Institute, Inc.).

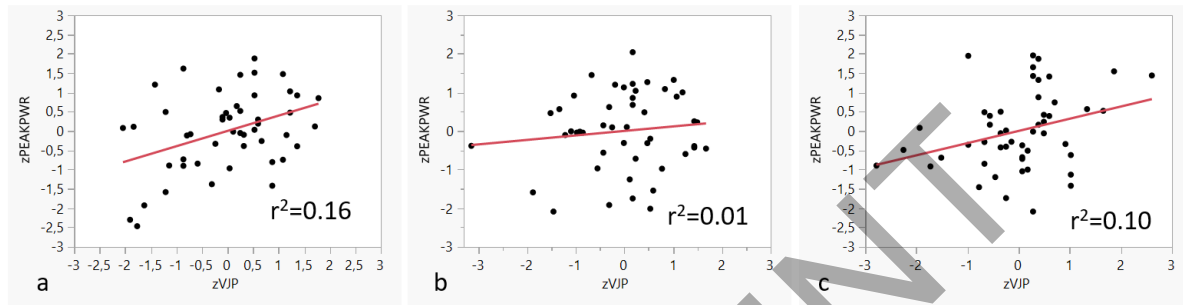
179
 180 The second set of analyses corresponds to experiment 2. Figure 2a shows the adjusted line for
 181 zPEAKPWR as predicted by zVJP, according to model $zPEAKPWR = k + s(zVJP) + \text{participant} + \text{Error}$.
 182 The association is strong with an $R^2 = 0.9891$ ($p < 0.0001$); the intercept (0.0109) is not different from 0 (p
 183 = 0.2101). The slope (0.2010), however, is different from 1 ($p = 8.58 \times 10^{-20}$). Figure 2b shows the adjusted
 184 line for zMEANPWR as predicted by zVJP, according to model $zMEANPWR = k + s(zVJP) + \text{participant}$
 185 + Error. The association is strong with an $R^2 = 0.9617$ ($p < 0.0001$); the intercept (0.0075) is not different
 186 from 0 ($p = 0.6465$). The slope (0.4285), however, is different from 1 ($p = 8.8 \times 10^{-5}$).



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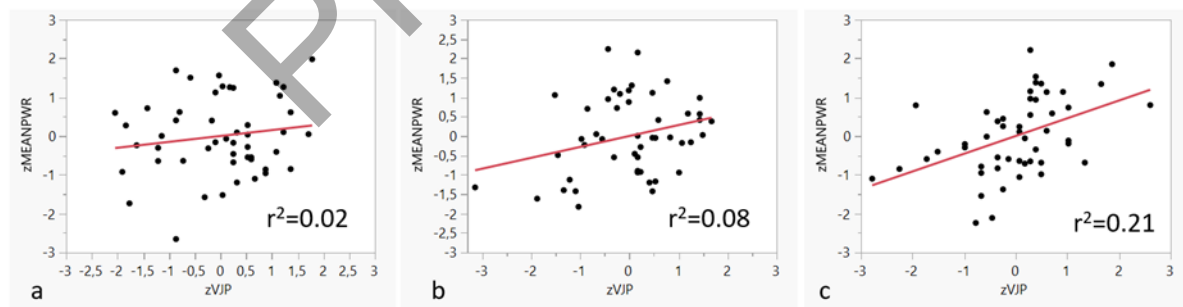
188 **Figure 2.** Prediction of normalized mechanical power from normalized vertical jump performance (zVJP).
 189 Experiment 2, within-subjects design, participants as random effects. Participants = 3. Trials = 50. (a) Peak
 190 mechanical power. Total valid data points: 147; $R^2 = 0.9891$; Intercept = 0.0109; Slope = 0.2010. (b) Mean
 191 mechanical power. Total valid data points: 147; $R^2 = 0.9617$; Intercept = 0.0075; Slope = 0.4285. Source.
 192 the authors. Figures were created using JMP Pro v.15.1.0 (SAS Institute, Inc.).

193 Figure 3 shows the individual bivariate adjustments for zPEAKPWR as a function of zVJP for
194 experiment 2. These individual models all resulted in Slopes $\neq 1$: 0.396, 0.116, and 0.352, for participants
195 DI07, DI10, and DI09, respectively ($p < 0.0001$). Models for DI07 and DI09 were statistically significant
196 ($p < 0.05$), but model for DI10 was not ($p = 0.4311$). The intercept was not different from 0 ($p = 1.000$) in any
197 of the models.



198 **Figure 3.** Individual bivariate adjustments for zPEAKPWR as a function of zVJP, experiment 2. (a)
199 Participant DI07. (b) Participant DI10. (c) Participant DI09. Source: the authors. Figures were created
200 using JMP Pro v.15.1.0 (SAS Institute, Inc.).
201
202

203
204 Figure 4 shows the individual bivariate adjustments for zMEANPWR as a function of zVJP, also for
205 experiment 2. These individual models all resulted in Slopes $\neq 1$: 0.152, 0.281, and 0.457, for participants
206 DI07, DI10, and DI09, respectively ($p < 0.0001$). The intercept was not different from 0 in all three models
207 ($p = 1.000$).



208
209 **Figure 4.** Individual bivariate adjustments for zMEANPWR as a function of zVJP, experiment 2. (a)
210 Participant DI07. (b) Participant DI10. (c) Participant DI09. Source: the authors. Figures were created
211 using JMP Pro v.15.1.0 (SAS Institute, Inc.).
212

213

214 Discussion

215 This study used regression analysis techniques to validate the use of vertical jump performance, or jump
216 height, as a predictor of lower limb mechanical power in humans. In line with previous studies evaluating
217 regression equations based on VJP (Canavan & Vescovi, 2004; Sayers et al., 1999; Tessier et al., 2013), the
218 association between VJP and mechanical power for 52 participants doing 5 vertical jumps each was shown
219 to be statistically significant and, more than that, considerably high, with coefficients of determination
220 higher than 0.92. Even with a small sample of three participants, who performed 50 vertical jumps each, the
221 models were statistically significant and showed coefficients of determination higher than 0.96.
222 Nevertheless, the models in the present study were evaluated using standardized scores (zVJP, zPEAKPWR,
223 and zMEANPWR), and therefore were expected to result in an intercept = 0 and a slope = 1. Intercepts were
224 indeed not statistically different from 0, but the slopes were different from 1 in all cases for these group
225 regressions. This is additional evidence supporting the recent claim that VJP is not an accurate predictor of
226 mechanical power (Morin et al., 2019; Tessier et al., 2013).

227 This manuscript used Vertical Jump Performance (VJP) as the predictor variable. VJP was calculated
228 very precisely, but in daily life, common practice by coaches and trainers involves estimating vertical jump
229 height (JUMPAIR) from time in the air, that is, the flight time during the jump, a much more practical test.
230 We performed the same analyses as those described for experiment 1, but using zJUMPAIR as the major
231 predictor. The results were very similar to those obtained from zVJP, showing excellent coefficients of
232 determination for both the zPEAKPWR ($r^2=0.97$) and the zMEANPWR ($r^2=0.92$) models ($p < 0.0001$),
233 while the slopes for these models were also statistically different from 1: 0.548 and 0.601, respectively ($p <$
234 0.0001). Therefore, the problem we have highlighted when predicting mechanical power from VJP occurs
235 also if one uses a jump height calculated from time in the air as the predictor.

236 The results were even more troublesome when each of the three individuals who performed 50 jumps
237 was analyzed separately: all coefficients of determination were considerably attenuated, despite using
238 standardized scores for the models; the zPEAKPWR model was not significant for one of the participants,
239 while the zMEANPWR model was not significant for two participants. To make matters worse, all the

240 slopes for these models were statistically different from 1. These results are solid evidence that the
241 association between jump height and mechanical power in humans is much weaker than previously shown.
242 For different jumps, the amplitude of the push-off movement, and the corresponding time, can be shorter or
243 longer, but if the work performed is the same, the power will be higher or lower, respectively (Morin et al.,
244 2019); meanwhile, VJP will stay the same. Each individual has different strategies for achieving the same
245 jump height (Aragón-Vargas LF & Gross MM, 1997b), but this fact is masked by the large differences
246 between participants in conventional regression analysis with groups. Given that the main use of power tests
247 is to monitor individual progress, applying the strength of the association from large groups to individuals
248 makes no sense.

249 An additional comment is warranted regarding the mistake of using flight time for the mathematical
250 calculation of power, due to its prevalence. The logic is as follows: to obtain power, you may divide the
251 work performed during push-off (propulsion) by the time required to perform it. If you know the
252 participant's vertical jump height (h) and body mass (m), and the value of g (the acceleration due to gravity),
253 you can calculate work because the kinetic energy at takeoff (identical to the work performed during the
254 positive phase of pushing against the ground, or push-off) is all converted to potential energy at the instant
255 of peak height, that is, $m \cdot g \cdot h$. This is correct, but the problem is introduced in the next step: the time from
256 takeoff to the highest position during flight (or the time from the highest position to landing) is typically
257 estimated from $1/2$ of flight time. However, as has been pointed out before, when this time is used in the
258 calculation the result does not represent the power exerted by the jumper during push-off, but the average
259 power of the falling jumper (Harman et al., 1991). The calculation is useless because flight time is
260 necessarily associated with the height of the jump, according to the free-fall mathematical equation $h =$
261 $(g \cdot t_f^2)/2$, where t_f is the time from peak to landing. The power thus calculated has nothing to do with the
262 mechanical power exerted by the muscles during push-off, the variable of interest, because the incorrect
263 time is used; push-off time can only be obtained using sophisticated equipment. Unfortunately, this basic
264 mistake is widespread, even in textbooks (Rodríguez Zárate et al., 2018) (page 57, figure 20). The preceding
265 error is compounded by the fact that the time the body center of mass moves up or down during flight is not

266 ½ of the time in the air, as typically assumed, because jumpers normally leave the ground with their knees
267 and hips in full—or close to full—extension, but they land with their knees and hips partially flexed (Hatze,
268 1998). This is confirmed by our own unpublished calculations: with 256 jumps performed by 52 different
269 participants, the time of flight up (0.276 ± 0.027 s) is significantly different from the time of flight down
270 (0.302 ± 0.170 s, $p = 0.0155$).

271

272 Conclusions

273 In conclusion, vertical jump height should not be used to predict leg power because regression models
274 using standardized values of vertical jump and mechanical power for group data fail to meet the criterion of
275 a slope not different from 1, even though they result in high coefficients of determination. Furthermore,
276 common prediction equations are based on group data but are predominantly used to monitor individual
277 progress; prediction equations for individuals performing multiple jumps fail to meet the criterion of a slope
278 not different from 1 and result in poor coefficients of determination ($R^2 \leq 0.21$). Morin et al. (2019)
279 recommend some practical solutions to human power testing, based on previous publications by Samozino
280 et al. (2008) and Jiménez-Reyes et al. (2017); their approach should be evaluated using the same procedures
281 we have presented, with an emphasis on within-subject analysis. Such analysis may prove that the use of
282 Morin et al.'s approach is sound and useful for monitoring individual athletes. Meanwhile, we recommend
283 that whenever mechanical power results are to be used effectively, they should be obtained directly with the
284 use of a force platform or a kinematic analysis system. Jump height results should be reported, analyzed,
285 and interpreted only as vertical jump performance.

286

287 Practical implications

- 288 • Jump height is a poor predictor of leg power.
- 289 • Mechanical power should be measured directly with validated methods and instruments.

- 290 • Power and other performance prediction equations in exercise science should always be evaluated
291 using our within-subject analysis model, since they will mostly be applied to monitoring changes
292 in individual athletes.

293
294 **Conflict of interest:** No conflicts of interest, financial or otherwise, are declared by the authors. The authors
295 have no financial or other interest in the testing equipment or its distribution. All authors declare that the
296 results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate
297 data manipulation.

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