Allometric scaling for normalizing maximal oxygen uptake in elite rugby union players

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Summary

Introduction: The relation of a biological variable to body mass is typically characterized by an allometric scaling law. The purpose of this study was to evaluate the relationship between oxygen consumption (VO_{2max}), as a parameter of aerobic exercise performance, and body composition in rugby players.
Material and method: The sample included one hundred and seven males of the Spanish rugby team. Age: 25.1 ± 3.4 years; body mass (BM): 89.8 ± 11.7 kg, height: 182.4 ± 6.5 cm; 52 backs (BR) and 55 forwards (FR). Maximum oxygen consumption (VO_{2max}, $l.min^{-1}$) was measured during treadmill exercise test with progressive workload. Anthropometrical measurements were performed to estimate the fat-free mass (FFM) and muscle mass (MM). The allometric exponent "b" was determined from equation $y = a * x^b$; where "y" is VO_{2max} and, "x" is the corresponding mass (BM, FFM or MM) and "a" is one constant.
Results: The VO_{2max} was 4.87 ± 0.56 $l.min^{-1}$, BR vs FR, 4.67 ± 0.48 $l.min^{-1}$ vs 5.06 ± 0.06 $l.min^{-1}$; FFM: 77.5±7.7 kg, 73.5±7 kg vs 81.3±6.3 kg; and MM: 52.9±6.5 kg, 49.6±5.6 kg vs 56.1±5.8 kg. The allometric exponents ($p < 0.0001$; $R^2 = 0.4$) were: 0.58 for BM (95% CI: 0.45 - 0.72); 0.71 for FFM (95% CI: 0.53 - 0.90); and 0.58 for MM (95% CI: 0.43 - 0.73). Significant differences ($p < 0.0001$) were found BR vs FR according to their anthropometric characteristics and VO_{2max} with respect to BM and MM without allometric scaling. While the VO_{2max} indexed by means of allometric scaling was similar between BR and FR.
Conclusions: In comparative studies, the VO_{2max} should be expressed proportional to the 0.58 power of body mass or related to FFM in order to take into account the variability in of body composition in rugby players.

Key words:
Allometric. Body size. Oxygen uptake. Rugby union. Body composition. Maximal aerobic capacity. Team sports.

Normalización del consumo de oxígeno máximo por escala alométrica en jugadores de rugby unión de élite

Resumen

Introducción: La relación de una variable biológica con la masa corporal se caracteriza típicamente por una ley de escala alométrica. El propósito del estudio fue evaluar la relación entre el consumo máximo de oxígeno (VO_{2max}), como parámetro de rendimiento aeróbico, y la composición corporal en jugadores de rugby.
Material y método: La muestra incluyó a 107 varones de la selección española de rugby. Edad: 25,1 ± 3,4 años; masa corporal (MC): 89,8 ± 11,7 kg, talla: 182,4 ± 6,5 cm; 52 defensas (DF) y 55 delanteros (DL). El VO_{2max} ($l.min^{-1}$) se determinó en tapiz con carga progresiva hasta el máximo esfuerzo. Mediante técnica antropométrica se estimó la masa libre de grasa (MLG) y la masa muscular (MM). El exponente alométrico "b" se determinó por la ecuación $y = a * x^b$; donde "y" es VO_{2max}, "x" es la masa correspondiente (MC, MLG o MM) y "a" es una constante.
Resultados: El VO_{2max} fue 4,87 ± 0,56 $l.min^{-1}$, DF vs DL, 4,67 ± 0,48 $l.min^{-1}$ vs 5,06 ± 0,06 $l.min^{-1}$; MLG: 77,5 ± 7,7 kg, 73,5 ± 7 kg vs 81,3 ± 6,3 kg; y MM: 52,9 ± 6,5 kg, 49,6 ± 5,6 kg vs 56,1 ± 5,8 kg. Los exponentes alométricos ($p < 0{,}0001$; $R^2 = 0{,}4$) fueron: 0,58 para MC (IC 95%: 0,45 - 0,72); 0,71 para MLG (IC del 95%: 0,53 - 0,90); y 0,58 para MM (IC del 95%: 0,43 - 0,73). Se encontraron diferencias significativas ($p < 0{,}0001$) DF vs DL según sus características antropométricas y VO_{2max} con respecto a BM y MM sin escalado alométrico. Mientras que el VO_{2max} indexado mediante escalado alométrico fue similar entre DF y DL.
Conclusiones: En estudios comparativos el VO_{2max} debería expresarse a la potencia de 0.58 de MC o con MLG debido a la variabilidad de la composición corporal en jugadores de rugby.

Palabras clave:
Alométrico. Tamaño corporal. Consumo de oxígeno. Rugby unión. Composición corporal. Capacidad aeróbica máxima. Deportes de equipo.

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Introduction

In the evaluation of the physiological variables influencing sports performance, such as maximal oxygen uptake (VO_{2max}), the interpretation may differ depending on whether it is expressed in absolute terms ($l*min^{-1}$) or in comparison to body mass ($ml*kg^{-1}*min^{-1}$). The dependency between a biological variable such as VO_{2max} (y) and body mass (x) can be expressed through allometric scaling in the form $y = a * x^b$, where b is the exponent or power of the scaling. When we express oxygen uptake as $ml*kg^{-1}*min^{-1}$, the exponent "b" is assumed to be equal to 1 with allometric scaling. However, most of the research conducted in this field suggests that "b" is less than 1, somewhere between 0.81 and 0.59 of body mass[1-4], as the rate at which oxygen uptake increases is less than the rate of increase in body mass. In an extensive sample of Danish athletes covering 25 different athletic activities, Jensen *et al*., 2001[5] estimated a power close to 0.73 between body mass and VO_{2max} determined in a maximum stress test. Because of this, depending on the normalization model or scaling we apply, we might have a bias according to the physical characteristics of the subject, potentially making this a factor affecting the comparisons made among individuals and also in longitudinal studies. On the other hand, body mass represents the sum of both fat mass and fat-free mass, in which the latter is the metabolically active one because of its muscular component. Athletes may have the same body mass with different proportions of fat mass and fat-free mass; and also the same VO_{2max} in absolute terms but different in relative value, so comparisons may be equivocal if the effect of these variables is not considered. In a recent review by Lee and Zhang, 2021[6] they conclude that the most appropriate relationship between VO_{2max} and body weight is the power function and hypothesize that the b-value may not be a static value but a dynamic value ($\geq 2/3$ b <1); they also suggest that lean weight is better for standardizing VO_{2max}. Regarding this, Lolli *et al.,* 2017 found an exponent of 0.90, with a 95% CI 0.68 to 1.12 by means of a meta-analysis based on fifteen previous fat-free mass studies[7]. The normalization of oxygen uptake in relation to fat-free mass has been called "aerobic muscle quality", indicating that it could be useful to make better comparisons of VO_{2max} among participants of varying fat and body mass[8,9].

Rugby is a contact team sport in which, in its 15-player version (rugby union, "RU"), players have quite distinct physical characteristics depending on their position on the field of play. They are divided into two large groups, the forwards (three lines making up the scrum of eight players) and the backs or three-quarters line (seven players). While the forwards are heavier, taller, with more subcutaneous adipose tissue, and require greater power and muscle strength, the backs are lighter, with less fat and need more speed and agility on the field[10-16]. Matches last for 80 minutes, divided into two halves with a 15 minute rest, so both groups must have good aerobic capacity. Rugby is an alternating aerobic-anaerobic activity with high demand of repeated-high intensity efforts and frequent collisions. Performance is associated with lower-body strength and power, high speed, high acceleration, and lower percent body fat[17-19]. Players can cover an average of 7 km during play; of this distance, 11% high intensity; the backs perform a greater number of sprints than forward. Mean game heart rate is around 88% HR_{max} [20]. The training and physical preparation of rugby players will be aimed at improving their skills, including strength, by increasing the fat-free mass[21], Also the contemporary rugby union player runs longer and harder. A relationship has been established between skinfolds and fat percentage to the performance of professional players[16]. Their body composition may undergo changes in the course of the season and the player's sporting life[22-25]. Currently there are few studies in rugby players in which the oxygen uptake values are determined directly by ergoespirometry, being estimation by test or physical tests the usual. On the other hand, the references of body composition are diverse when estimating body fat by different techniques and models[26, 27].

The aim of this study was to determine the allometric ratio of VO_{2max} to body mass, fat-free mass and muscle mass in high-competition rugby players and to analyse which parameter would better discriminate the changes in performance monitoring.

Material and method

A retrospective study was carried out on the members of the male national rugby teams sent to the Sports Medicine Centre by their federation for a medical and sports examination during the period from 1994 to 2017. First of all, we selected for each player the stress test in which they obtained the highest VO_{2max} ($l*min^{-1}$) in the period mentioned, for a cross-sectional study in order to obtain the reference values. This sample reached a total of 107 players, of whom 55 were forwards (FR) and 52 backs (BR), with a mean age of 25.1 ± 3.4 years, mass 89.8 ± 11.7 kg and height 182.4 ± 6.5 cm. In this group, we determined the allometric exponent for subsequent application to the VO_{2max} values relative to the different masses.

Secondly, for the longitudinal study, we selected the rugby players called up on two or more occasions, choosing for each one the two checks at which they achieved the highest (C1) and the lowest (C2) values for VO_{2max} in absolute figures for the stress test. This sample comprised 17 players, of whom twelve were BR and five FR.

The anthropometric protocol included the following variables: body mass (kg), height (cm), skinfolds (iliac crest, supraspinal, abdominal, subscapular, biceps, triceps, front thigh and medial calf, in mm) and girths of the forearm, middle thigh and maximum leg (cm). The material used was: Seca scales; Holtain stadiometer; Holtain skinfold caliper; and Rosscraft anthropometric tape. The person taking the measurements was accredited to level III by the ISAK (International Society for the Advance of Kinanthropometry), with the measurements being taken according to the recommendations of this society[28], except for the measurement of the perimeter of the medial thigh[29].

The study of body composition was carried out by the anthropometric technical, with body density being estimated using the equation of Withers *et al*. (1987) and subsequently the percentage of fat using the formula of Siri, (1961) both cited in Norton, 1996[30]; fat masses (FM) and fat-free masses (FFM) were then derived. Muscle mass (MM) was estimated using the equation of Martin *et al*. (1990)[29].

The stress test was carried out on a treadmill (Jaeger, LE 600 C model), using Jaeger Oxycon Champion and Jaeger Oxycon Pro respiratory gas analysers depending on the year of each control. After two minutes in the initial phase at 6 km/h, the first stage began at 8 km/h. The speed increases were 0.25 km/h every 15 seconds with a constant slope of 1% until exhaustion. The parameters evaluated include: heart rate (HR, bpm), absolute VO_{2max} ($l*min^{-1}$) and the VO_{2max} ($ml*kg^{-1}*min^{-1}$) relative to body mass (BM), fat-free mass (FFM) and muscle mass (MM). The aerobic-anaerobic transition was determined from ventilation and gas exchange[31]. The ventilatory threshold [1] (VT1) was defined as the first non-linear increase in ventilation with an equivalent increase in oxygen (VE/VO2) without any concomitant increase in the equivalent CO2 (VE/VCO2). Ventilatory threshold 2 (VT2) was considered to be the second non-linear increase in ventilation with a non-linear increase in the VE/VO2 ratio and a simultaneous increase in the VE/VCO2 ratio. The total duration of the test (FT, final time) and the time at which the VT2 was set (ANT, anaerobic threshold time) were considered as the comparative parameters for maximal power and sub-maximal capacity respectively in the longitudinal study as the same protocol was applied in all tests.

The sportsman signed an informed consent form in which they assigned the results of their tests for research purposes on condition of confidentiality for their personal details. The research work was carried out in accordance with the ethical standards of the Helsinki Declaration.

Descriptive statistical treatment (mean, standard deviation and percentiles) was carried out, with the normality of each of the variables being determined by the Shapiro-Wilk test. The difference between the FR and BR in the transversal sample was confirmed using the T test for independent samples or the Mann-Whitney U test in those that did not meet the criteria for normality. In the longitudinal study of the 17 players, Wilcoxon's non-parametric test was used between C1 and C2. Effect sizes can be evaluated using the r index and are classed as small (0.10-0.29), medium (0.30-0.49), or large (0.50 and greater)[32]. VO_{2max} values were assessed according to the percentiles established.

The potential curvilinear regression model was developed according to the allometric model, $y = a * x^b$, where absolute VO_{2max} was the dependent variable "y"; the different masses (body mass, fat-free mass and muscle mass) were the independent variables "x"; "b" was the exponent of power, and "a" the proportionality constant, using the Napierian logarithms of these variables for transformation to a linear adjustment. The VO_{2max} were subsequently calculated relative to the powers obtained. By means of this correlation, it was possible to study the independence of the new indices with the corresponding masses.

Statistical significance was considered to exist above a *p* value of 0.05. Analyses were conducted using IBM SPSS Statistics version 19.

Results

The allometric exponents calculated in the regression study ($P < 0.0001$; $R^2 = 0.4$) were 0.58 (95% CI: 0.45-0.72) for BM; 0.71 (95% CI: 0.53-0.90) for FFM; and 0.58 (95% CI: 0.43-0.73) for MM. The regression curves are shown in Figure 1. The correlation of the relative VO_{2max} calculated using allometric scaling with their corresponding masses turned out to be not significant (p between 1 and 0.94) and with an $R^2 = 0.0001$, confirming the independence of the new indices.

Table 1 shows the anthropometric characteristics and the VO_{2max} of the entire cohort and grouped by playing positions (FR and BR). Significant differences were found between both groups in all the anthropometric variables, with the FR being heavier, taller, with a higher percentage of fat, fat-free mass and muscle mass than the BR. With respect to the maximal oxygen uptake, there is a significant difference between the two groups when their VO_{2max} values are assessed in absolute terms, as well as by BM and MM, but not by FFM. FR players have higher VO_{2max} values in absolute terms, whereas in relative terms, the BR have better VO_{2max} values compared to BM and MM. When allometric scaling is applied to relative uptakes, the differences between the two groups disappears for BM, FFM and MM, with all of them giving similar values. The effect size in VO_{2max} relative to masses using allometric scaling is virtually zero, while the effect size is medium with respect to body mass. The percentiles of VO_{2max} obtained with the 107 players in absolute values and with respect to the various masses (BM, FFM and MM) using linear and allometric scaling are shown in Table 2.

Figure 1. Relationships between VO_{2max} ($l*min^{-1}$) and body mass (kg), fat-free mass (kg) and muscle mass (kg) for 107 male rugby players; *P* <0.0001.

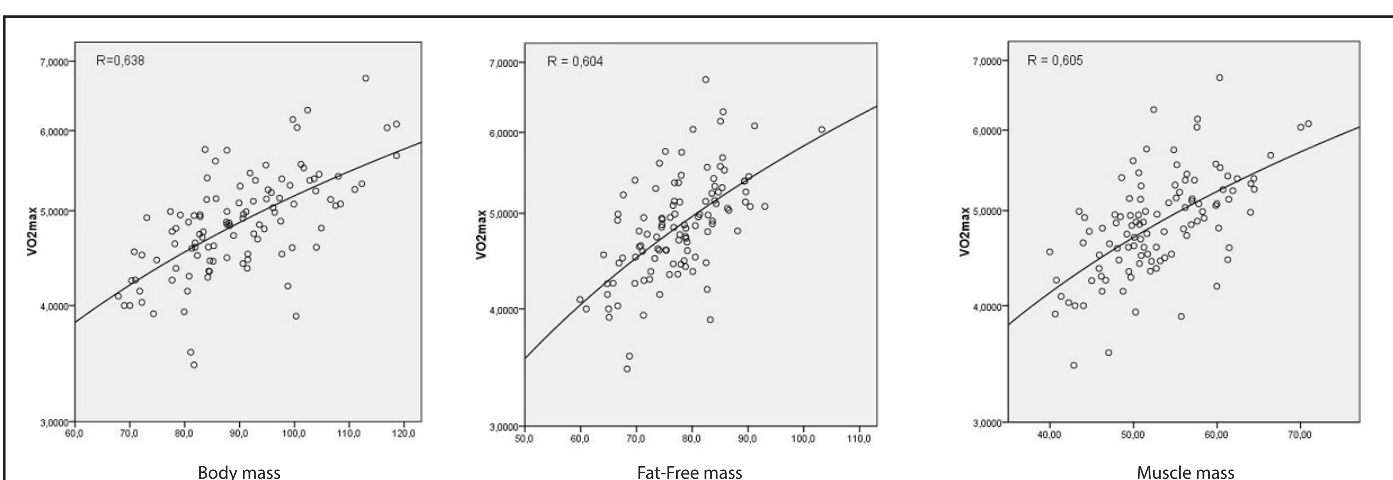

Table 1. Anthropometric and physiological characteristics of rugby union players (mean±SD).

	Total (n = 107)	BR (n = 52)	FR (n = 55)	*P*	r
Body mass (kg)	89.8±11.7	82.7±8.9	96.6±9.8	0.000	-0.66
Height (cm)	182.4±6.5	180±6.1	184.7±6.2	0.000	0.36
Body fat (%)	13.2±4.9	10.8±3.3	15.5±5.1	0.000	0.48
FFM (kg)	77.5±7.7	73.5±7	81.3±6.3	0.000	0.51
MM (kg)	52.9±6.5	49.6±5.6	56.1±5.8	0.000	0.50
VO_{2max}. ($l*min^{-1}$)	4.87±0.58	4.67±0.48	5.06±0.6	0.000	0.34
VO_2 isometric scaling					
VO_{2max}. $ml*kgBM^{-1}*min^{-1}$	54.6±5.7	56.73±4.99	52.55±5.6	0.000	0.37
VO_{2max}. $ml*kgFFM^{-1}*min^{-1}$	63.0±6.27	63.74±5.59	62.30±6.83	0.236	0.11
VO_{2max}. $ml*kgMM^{-1}*min^{-1}$	92.58±9.99	94.65±9.12	90.61±10.46	0.036	0.20
VO_2 allometric scaling					
VO_{2max}. $ml*kgBM^{-0.58}*min^{-1}$	352.9±31.7	354.96±28.11	350.87±34.93	0.508	0.06
VO_{2max}. $ml*kgFFM^{-0.71}*min^{-1}$	218.3±20.8	217.53±17.87	218.95±23.36	0.726	0.03
VO_{2max}. $ml*kgMM^{-0.58}*min^{-1}$	486.2±46.1	484.17±40.27	488.14±51.36	0.659	0.04

BM: body mass; Body fat (%) estimated by Withers *et al.* 1987, in Norton, 1996[30]; FFM: fat-free mass; MM: muscle mass, estimated by Martin *et al*. 1990[29]. p, significantly different between BR (backs) and FR (forwards). r effect size: small, <30; medium, 0.30–0.49; and large, 0.50 and greater[21].

Table 2. Percentiles of absolute and relative VO_{2max} for rugby union players (n = 107).

	VO_{2max}	VO_{2max} relative					
Percentile	$l*min^{-1}$	BM	BM^{as}	FFM	FFM^{as}	MM	MM^{as}
3	3.90	42.80	277.05	50.98	175.33	73.23	388.69
5	3.96	44.80	304.93	54.24	188.80	76.67	406.13
10	4.14	47.25	317.09	56.04	196.04	82.59	441.07
15	4.28	48.76	323.71	57.07	199.01	83.52	444.15
20	4.40	50.13	329.74	58.12	202.80	84.51	450.90
25	4.48	51.10	334.49	58.75	205.25	85.22	457.95
30	4.56	51.54	336.58	60.13	208.49	86.15	462.68
35	4.61	52.11	342.06	60.28	210.04	87.38	468.31
40	4.72	52.94	345.14	60.94	212.41	88.89	470.65
45	4.80	54.18	350.33	61.24	213.79	90.63	476.36
50	4.86	54.69	353.50	61.96	216.13	92.07	482.74
55	4.92	55.07	355.43	62.84	218.25	93.45	487.98
60	4.98	55.71	358.17	64.42	220.28	93.98	494.51
65	5.06	56.63	360.16	65.00	221.84	95.38	499.00
70	5.13	57.50	366.41	65.56	224.75	96.48	506.19
75	5.23	59.21	373.87	66.33	228.99	98.24	511.64
80	5.33	59.84	375.26	66.86	232.18	101.12	516.91
85	5.41	60.39	381.49	69.37	239.38	103.89	523.99
90	5.57	61.40	389.84	72.52	246.62	106.63	547.39
95	6.04	64.35	417.67	75.48	259.67	111.66	575.59
97	6.13	65.44	420.86	76.94	262.86	113.33	582.82

VO_{2max} relative: BM, body mass: $ml * BM^{-1} * min^{-1}$; BM^{as}: $ml * BM^{-0.58} * min^{-1}$; FFM, fat-free mass: $ml * FFM^{-1}*min^{-1}$; FFM^{as}: $ml*FFM^{-0.71}* min^{-1}$; MM, muscle mass: $ml * MM^{-1}* min^{-1}$; MM^{as}: $ml* MM^{-0.58}* min^{-1}$. Superscript "as": allometry scale. BM, FFM and MM in kg.

Table 3 shows the mean values for the anthropometric and ergospirometric readings of the 17 players selected to take part in the longitudinal study. There are significant differences in BM but not in the percentage of fat, FFM and MM. The VO_{2max} values show differences in both the absolute and the relative values, with or without allometric scaling. The FT and ANT times gave a similar mean in both controls. The effect size is large in BM and in VO_{2max}, confirming the differences mentioned. Table 4 shows the same data individually for each player in the two controls, ranked by larger to lower VO_{2max} ($l*min^{-1}$) (C1 and C2). Taking a difference of more than or equal to 5% as the criterion, eight players (47%) were found to have changes in their VO_{2max} ($l*min^{-1}$), of whom five also showed variation with respect to body mass ($ml*kg^{-1}*min^{-1}$). Two players (11.8%) had variations in their VO_{2max} ($ml*kg^{-1}*min^{-1}$) but not in VO_{2max} ($l*min^{-1}$). Lastly, seven players (41.2%) showed no change in their VO_{2max} values in either absolute terms nor in relation to their body mass.

If we analyse the trend in the variables of those subjects with the greatest variations in their body composition and/or in the oxygen uptakes, we can examine if there are differences in the valuation made with respect to the established references depending on whether we estimate it with or without an allometric scale. Four of these cases are reviewed below.

Subject nº 1 gained 3.5 kg of body mass, corresponding to an increase in the fat component, and raised the percentage of fat by 2.7; the fat-free and muscle mass components were similar in both controls. In the stress test, he produced a shorter time, achieving a lower VO_{2max} in both absolute terms (a decline of 20 p) and also relative to body mass (a decline of 15 p). If we see the change in VO_{2max} with respect to BM using allometric scaling, he goes from being on the upper limit to a low range (a decline of 70 p), the same as if we value it with respect to MM with or without scaling. As for VO_{2max} with respect to FFM, the valuation ranges from high to low (60-65 p) and from high to medium (55 p), respectively with or without scaling. With respect to the sub-maximal values, the anaerobic threshold represented by VT2 in the 2nd control was reached 1 min sooner, therefore at a lower speed. In this case, there is an unfavourable evolution in his physical condition (an increase in fat mass and lower values for maximal and sub-maximal oxygen uptake), which is discriminated better with allometric scaling or by relating it to FFM.

Subject nº 2 lost 4.1 kg of body mass, all corresponding to the fat component, reduced the percentage of fat by 3.6 and increased the non-fat component by 0.6 kg. In the stress test, the FT was similar and there were no significant changes in the absolute VO_{2max} (it fell by between 5 and 10 p) or with respect to BM without scaling (5 p) or with scaling (equal to p). With respect to the FFM with or without scaling, his values come down in a similar way (10 p), passing from the medium to low range in the valuation of allometric FFM. In comparison with MM, he remained in the low range at both controls, without scaling (5 p) and with scaling (10 p). As for the sub-maximal values, the anaerobic threshold in the second control was reached 1.15 min later, at a higher speed. In other words, the better body composition was only reflected in the stress test in the sub-maximal values, with the most evident changes being in related to FFM and MM.

Subject nº 4 lost 3.2 kg of body mass, of which 1.3 kg corresponded to the fat-free component and 1.9 kg to the fat component, lowering the fat percentage by 2.3. In the stress test he lowered his VO_{2max} in all variables: absolute (25 p) and relative to BM without (20 p) or with scaling (35/40 p); relative to FFM without (30 p) or with scaling, it comes down (40/45 p), and with respect to MM without scaling (10 p) and with scaling (30 p). With respect to the sub-maximal values the anaerobic threshold in the second control was reached at almost the same time, 0.45 min afterwards. In other words, the changes in body composition (both components came down) were associated with lower maximal values in the stress test, all of which were more evident in comparison with FFM and BM using scaling.

In Subject nº 15 the greatest variation in absolute VO_{2max} was obtained during the stress test. He had lost 2.6 kg in mass, with 2.2 kg corresponding to fat mass, lowering the fat percentage by 2. This

Table 3. Longitudinal study of body composition and VO_{2max} (n =17).

		mean	SD	P	r
Body mass kg	C1	90.65	14.88	0.039	-0.50
	C2	88.79	14.62		
Body fat %	C1	12.99	5.01	0.121	-0.39
	C2	11.99	4.80		
FFM kg	C1	78.34	9.60	0.287	-0.26
	C2	77.70	10.21		
MM kg	C1	54.19	9.83	0.068	-0.42
	C2	53.34	9.38		
VO_{2max} $l*min^{-1}$	C1	4.93	0.54	0.000	-0.88
	C2	4.59	0.51		
VO_{2max} $ml*kgBM^{-1}*min^{-1}$	C1	54.86	4.39	0.010	-0.63
	C2	52.24	5.00		
VO_{2max} $ml*kgFFM^{-1}*min^{-1}$	C1	63.05	3.40	0.003	-0.73
	C2	59.36	4.72		
VO_{2max} $ml*kgMM^{-1}*min^{-1}$	C1	92.16	8.89	0.006	-0.67
	C2	87.21	9.35		
VO_{2max} $ml*kgBM^{-0.58}*min^{-1}$	C1	355.25	18.08	0.001	-0.80
	C2	335.19	22.83		
VO_{2max} $ml*kgFFM^{-0.71}*min^{-1}$	C1	218.97	10.96	0.001	-0.80
	C2	205.50	14.19		
VO_{2max} $ml*kgMM^{-0.58}*min^{-1}$	C1	486.37	26.67	0.001	-0.80
	C2	457.35	33.31		
Final time min	C1	9.60	0.93	0.365	0.19
	C2	9.79	1.12		
VT2 time min	C1	6.76	0.97	0.602	0.07
	C2	6.84	1.01		

The two checks where they achieved the highest (C1) and the lowest (C2) VO_{2max} in absolute values. BM: Body mass; FFM: fat-free mass; MM: muscle mass; VT2: ventilatory threshold 2; p: statistically significant; r: (z/√n); effect size: small, <30; medium, 0.30–0.49; and large, 0.50 and greater[21]. % body fat estimated by Withers *et al*. 1987, in Norton 1996[30] and MM by Martin *et al.* 1990[29].

Table 4. Longitudinal study: individually data for each player in the two controls.

Subjects		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
BM	C1	118.6	108	117.6	73.3	74.1	86	104	85.3	88.8	90.7	97.7	71	72.2	83.7	97.8	84	88.2
kg	C2	122.1	103.9	109.7	70.1	68.9	88.2	98.8	84.3	84.9	92	97.1	73.5	71.8	82.8	95.2	84.2	82.8
Body fat	C1	23.1	23.2	18	11.2	12.6	10.9	18.4	13.5	10.7	10.6	8.5	7.3	7.7	8.1	12	15.2	9.7
%	C2	25.8	19.6	10.1	8.9	11.1	10.1	16.7	12.1	10.6	10.7	8.4	8.6	8.8	8.1	10	15.3	9.9
FFM	C1	91.2	82.9	96.4	65.1	64.8	76.6	84.9	73.8	79.3	81.1	89.4	65.8	66.6	76.9	86	71.3	79.7
kg	C2	90.6	83.5	98.7	63.8	61.3	79.3	82.3	74.1	75.9	82.1	89	67.2	65.5	76.1	85.7	71.4	74.6
MM	C1	70.96	64.11	71.28	43.82	44.76	50.01	67.02	50.05	51.41	52.82	62.43	40.76	42.23	49.11	59.27	49.76	51.47
kg	C2	70.91	61.9	68.27	41.25	42.55	53.25	62.99	50.47	49.81	55.18	61.91	42.03	41.31	47.76	58.38	49.67	48.43
VO_{2max}	C1	6.09	5.37	5.35	4.59	4.12	5.02	5.22	4.61	4.89	4.96	5.38	4.25	4.03	5.18	5.32	4.39	4.98
$l*min^{-1}$	C2	5.24	5.23	4.76	4.09	4.01	4.84	4.9	4.42	4.36	4.8	5.23	3.69	3.82	4.95	4.57	4.28	4.93
VO_{2max}BM	C1	51.32	49.7	45.47	62.59	55.59	58.38	50.14	54.02	55.09	54.66	55.05	59.87	55.82	61.9	54.36	52.27	56.47
$ml*min^{-1}*kg^{-1}$	C2	42.91	50.36	43.38	58.4	58.13	54.82	49.64	52.37	51.38	52.19	53.85	50.26	53.2	59.82	47.97	50.82	59.54
VO_{2max}FFM	C1	66.76	64.75	55.45	70.49	63.6	65.54	61.46	62.42	61.67	61.13	60.19	64.6	60.47	67.38	61.79	61.63	62.52
$ml*min^{-1}*kg^{-1}$	C2	57.83	62.64	48.24	64.13	65.39	60.99	59.58	59.57	57.45	58.46	58.77	54.99	58.34	65.12	53.32	59.97	66.05
VO_{2max}MM	C1	85.78	83.74	75.01	104.71	92.02	100.41	77.82	92.07	95.16	93.86	86.14	104.3	95.43	105.5	89.69	88.25	96.77
$ml*min^{-1}*kg^{-1}$	C2	73.88	84.53	69.71	99.26	94.13	90.8	77.85	87.48	87.57	87.01	84.46	88.02	92.47	103.7	78.23	86.16	101.8
VO_{2max}BMas	C1	374.2	348.6	330.4	373.6	333.3	372.4	346.2	343.4	356.1	356.5	370.3	352.7	331.1	390.4	365.8	330.2	364.1
$ml*min^{-1}*kg^{-0.58}$	C2	316.7	347.5	306.2	342.2	338.1	353.4	335.4	331.3	326	342.4	361.3	306	314.8	375.6	319.2	321.3	373.9
VO_{2max}FFMas	C1	242.7	229.1	204.8	232.7	209.7	226.7	218.9	213.6	215.4	214.9	217.5	213.9	201	233.3	220.9	208.8	218.7
$ml*min^{-1}*kg^{-0.71}$	C2	209.8	222.1	179.3	210.5	212.1	213	210.3	204.1	198.2	206.2	212.1	185.3	192.9	224.8	190.4	203.2	226.7
VO_{2max}MMas	C1	511.6	478.6	448.3	510.3	452.5	517.2	453.2	474.4	495.9	494.7	486.9	493.1	458	539.3	496.1	453.6	504.5
$ml*min^{-1}*kg^{-0.58}$	C2	440.5	476.1	409.1	471.6	453.1	480.2	441.7	452.3	450.3	467.1	475.8	423.1	439.7	524	430	442.5	517.4
Final time	C1	8.30	8.58	8.04	10.05	9.05	11.02	8.01	9.01	10.05	10.57	9.59	10.09	10.54	10.24	10.03	10.03	10.04
min	C2	7.02	9.01	9.07	11.47	9.05	11.43	10.02	10.00	10.03	10.29	9.58	9.04	10.03	10.13	11.03	10.05	10.10
VT2 time	C1	6.45	6.00	5.30	8.00	7.15	8.30	5.45	7.30	7.00	8.45	7.15	6.30	7.00	6.45	7.00	5.15	6.45
min	C2	5.45	7.15	5.00	8.45	6.00	7.15	7.15	7.45	7.30	8.15	6.45	6.15	6.30	7.00	8.45	6.45	7.00

Ranked by larger to lower VO_{2max} ($l*min^{-1}$) (C1 and C2). BM: body mass; % Fat estimated by Withers *et al.* 1987, in Norton 1996[30]. FFM: fat-free mass; MM: muscle mass by Martin *et al.* 1990[29]; Final time, duration of the stress test; time at which the VT2 was set (ventilatory threshold 2, anaerobic threshold). Superscript "as", allometry scale.

player achieved lower scores in all the VO_{2max} variables, moving from being in the high to the medium range in absolute terms (50 p), and lowering them in terms of BM without scaling (35) or with scaling (55 p); with regard to FFM, they were lowered without (40 p) or with scaling (50/55), and also for MM without scaling (35 p) and with scaling (50 p). With respect to the sub-maximal values, VT2 at the second control was reached 1.45 min later, at a higher speed. The improvement in body composition was accompanied by a worse stress test in comparison with the maximal values but with an improvement in sub-maximal capacity. The difference between the two controls in terms of the drop in VO_{2max} percentiles was greater with respect to BM and FFM with allometric scaling.

Discussion

In this study, we provide the percentiles of VO_{2max} for use in the assessment of RU players and recommend the use of VO_{2max} relative to fat-free mass or relative to body mass with application of scaling depending on whether or not a body composition study is performed. The investigation carried out on a large sample of rugby players, who differ in their morphology according to playing position, has shown that when we value oxygen consumption by body weight with a linear scale, it is underestimated in those of greater weight, since if an allometric scale is applied or we assess the oxygen consumption in relation to the fat-free weight, the differences between these players disappear

The classic studies on allometric ratios between oxygen uptake and BM set the value at 0.67 or 0.75[33-36]. Exponents less than 1 were also found in athletes, indicating that this ratio does not increase in proportion to BM during physical activity. Bergh *et al.* (1991)[3] obtained a power of 0.71 in VO_{2max} and 0.76 in $VO_{2submax}$ in endurance athletes. Svedenhag, 1995[37] also proposed that, for the correct assessment of runners, the oxygen uptake during a race should be expressed as $ml*kg^{-0,75}*min^{-1}$. The most wide-ranging study among sports practitioners was carried out by Jensen *et al.*, 2001[5], and the male group comprised 655 people engaging in 22 different types of sport subjected to stress tests with the corresponding specific ergometers. When the number of practitioners was large (n >100) as in the case of handball (n = 142, b = 0.72), cycling (n = 157; b = 0.74) and rowing (n = 117; b = 0.73), the allometric power came close to 0.73, so the authors set it at this value for the comparative studies between sports. Among Croatian athletes in different sports, Markovic *et al.,* 2009[38] obtained a power of 0.67. The mentioned researches did not include rugby, in which our power was lower (0.58). The potential reason is that rugby players are more robust, with a higher BM, entailing a higher fat and non-fat component than, for instance, among long-distance runners, cyclists or team sports players; on the other hand we consider the number of participants in our sample to be representative.

Secher, 1984[39] compared the relative oxygen consumption in rowers of different modalities (heavy and light) and therefore of different body size, with or without an allometric scale (b = 0.67), and also found that the differences disappeared with the allometric scale.

Our results are in agreement with von Döbeln[40] who already in 1957 had demonstrated, that VO_{2max} in 65 young men and women did not scale in direct ratio with body mass and should be expressed relative to FFM (body mass – fat mass), the exponent found to be 0.71 ± 0.082. On the other hand, Batterrham *et al.*[2] found that FFM models resulted in a larger coefficient of determination and a lower SE of the estimate in predicting VO2peak$_{2peak}$. Their findings, like ours, suggest that FFM estimates should serve as an indicator of body size; both studies conducted in the general population.

Therefore, we should apply independent indices among sports practitioners with major differences in mass or body composition in order to be able to use them for comparisons. If these are not available, the assessment of the athlete should always be made according to their playing position which, although not taking into account their body composition, is generally similar in terms of general morphological characteristics of mass and height.

An athlete's maximum aerobic power fundamentally depends on age, gender, genetic burden and the level of physical activity. It may be affected by changes in training and/or in body composition. Allometric models have been developed for VO_{2max} that also include other variables apart from FFM such as gender, height or age[41].

In an athlete, it may not be relevant how we express their absolute or relative oxygen uptake value over the course of a season or in successive years unless there are changes in mass or body composition. However, any modification of these parameters will influence their assessment. It has been found that among rugby players there has been an increase in BM in recent years, particularly among FRs, and this has been identified as one of the factors that determine improvement in sporting performance[25,42,43].

In the longitudinal study conducted, we have verified that when fat mass is lost and the percentage of body fat comes down, athletes improved their VT2 times. This coincides with the reports published by other authors[44,45] stating that the fat mass has no effect on VO_{2max} (aerobic power), so an excess of body mass at the expense of the fat component would not imply a lower VO_{2max}, although it might have a negative influence on the sub-maximal aerobic capacity.

The values reported for VO_{2max} are between 53 - 62 ml*kg^{-1}*min^{-1}. By playing position, FR are between 58 - 48 ml*kg^{-1}*min^{-1} and BR are between 60 - 55 ml*kg^{-1}*min^{-1} [17,46-50]. Our values are within these ranges.

The anthropometric characteristics are also similar to those reported by other authors[51,17,52,50,53], with a body mass of between 115-98 kg for FR and between 95-84 kg for BR and a height of between 190-183 cm among FR and between 182-178 cm for BR. When comparing the percentage of fat, attention must be paid to the technique and formula applied. Lundy *et al.,* 2006[54], in a sample of 74 Australian players, obtained an average estimated fat percentage, starting from different equations, of 11% among BR and 13.5% in the FR, percentages respectively similar to and slightly lower than those in the present study. Also similar to those reported by Carlson *et al.,* 1994[55] in BR (10%) and FR (13%) for the US team; and, also in the USA, Maud y Shultz, 1984[56] in BR (7.8%) and FR (10.5%). Similar values were obtained by Brewer *et al.,* 1994[57] and by Scott *et al.,* 2003[58] in BF (12.6 and 12.1%) and FR (15.2 and 16.1%) with British subjects, obtained by Durnin-Womersley, 1974. In 36 elite Spanish players, Suarez-Moreno and Nuñez, 2011[59] obtained by Yuhasz's E. a fat percentage of 12% in BR and 16.4% in FR. In Australia, Zemski *et al.,* 2015[12] used a DXA scanner (Hologic Discovery A, Hologic, Bedford, MA) and obtained 10,7% in BR and 14,2% in FR. La Monica *et al*. (2016)[50] in USA University students obtained an average of 8.8 vs 12.6% (BE vs FR) using Jackson-Pollock's E. Lastly, Posthumus *et al.,* 2020[16] in 39 players of New Zealand using DXA obtained the greatest fat percentage, 14.8% BR and 17.8% FR.

For rugby players, strength and muscle power are major components in their physical condition. Allometric studies have also been carried out[60- 62] to assess performance in various tests of the upper body (bench pressing) and the lower body (vertical jumping) with respect to BM, FR and BR, and it was found that the players were better characterized by the normalization using the corresponding power. Moreover, it was useful in the comparisons between those of different body sizes.

The limitations of the study include the errors inherent to the techniques used, mainly in connection with the anthropometric estimation of muscle mass, since three perimeters are involved in the equation applied (forearm, thigh and leg), all involving limbs, and this may under-estimate the calculation as it does not take into account the muscle development at trunk level that occurs in this form of sport. On the other hand, other factors implicated in VO_{2max}, such as central cardiovascular adaptation (cardiac volumes) blood parameters (haemoglobin) have not been assessed.

Among the practical applications of this work is the use of VO_{2max} percentiles provided for the assessment of RU players, advising the use of VO_{2max} relative to fat-free mass or scaled body weight according to assessment of body composition or not. Likewise, the data of fat percentage, lean mass and muscle mass can serve for the control and fixing of the objectives that the athlete can reach according to position and time of the season.

Allometric scaling will be more useful to us to discriminate the changes in the maximum oxygen consumption in relation to the body composition. The increase in VO_{2max} may be due to a greater mass of metabolically active tissue and/or greater ability to extract and use oxygen within the muscle, reflecting the metabolic adaptation. We recommend the use of lean weight to relativize the maximum consumption due to the limitations mentioned in the estimation of muscle mass. In comparative studies among athletes, a higher maximum oxygen uptake relative to lean weight will therefore tell us who has better metabolic adaptation and the changes of this with training.

Conclusion

In all medical controls of athletes, it would be desirable to be able to include most of the variables involved in or affecting performance in order to determine the suitability of the training carried out. Allometric scaling may be useful for distinguishing the variations in aerobic power when body mass is taken into account. An alternative would be to use fat-free mass or lean mass instead of body mass to relativize VO_{2max} since this takes into account biological variability in terms of body composition. The indices established with an allometric scale compensate for the effects of different body sizes and allow for comparative analysis betewen players.

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Conflict of interest

The authors do not declare a conflict of interest.

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