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PHYSICAL ANTHROPOLOGY

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Morphology, lower limbs performance and baropodometric characteristics of elite Brazilian Jiu-jitsu athletes

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Key words: foot support, anthropometric characteristics, somatotype, high performance

Abstract

Background. Brazilian jiu-jitsu (BJJ) athletes are characterized by the mesomorphic somatotype and require great muscular strength and power in the lower limbs in order to perform powerful offensive and defensive actions during combat. Moreover, both pressure and plantar support are very important and have a decisive role in increasing speed and stability during a fight.

Problem and Aim. Determine morphological and baropodometric characteristics of elite male BJJ athletes.

Methods. Sixteen elite BJJ performed the following test: body composition, unilateral and bilateral counter-movement jump and baropodometric assessment in static conditions.

Results. Athletes presented low body fat percentage (10.5 ± 2.2%) and balanced mesomorphic somatotype (2.2- 6.2-1.6). In lower limb strength performance, we observed measures of 41.9 ± 4.7 cm, 1713.4 ± 272 N, and 6.3 ± 4.3 % in vertical jump height, maximum force and low bilateral asymmetry index percentage respectively. Additionally, baropodometric analysis revealed higher maximum force values in heel and metatarsal zones ($p<0.05$), in pressure peak and load distribution in the non dominant foot ($p<0.05$). Moreover, we observed a higher load distribution percentage in the rearfoot surface than the forefoot surface in both the left (61.9% and 37.9%, respectively) and right foot (59.9% and 40.1% respectively).

Conclusions. Our results provide useful reference values for morphological and lower limb performance characteristics in elite male BJJ. Moreover, for the first time, baropodometric parameters were evaluated in this population, demonstrating that factors such as plantar pressure and plantar load distribution are greater in the non-dominant foot and in the rearfoot surface of both feet.

Introduction

The word Jiu-jitsu is made up of two words of Chinese origin: "Ju" which means soft and "jutsu" which refers to the technique [Andreato *et al.* 2016]. It is thought that the origin of Brazilian Jiu-jitsu (BJJ) was thanks to the Japanese Judoka Mitsuyo Maeda, known as Count Koma, who came to Brazil with the aim of teaching this soft art in this country [De Abranches A 2015]. The objective of the BJJ is the imposition of the combat technique on "brute force" because it uses biomechanics to empower the fighter's force and block that of the opponent [Souza *et al.* 2011]. In Jiu-jitsu, the intention to defeat the opponent is carried out through the submission of the opponent using techniques of projection, strangulation, immobilization and joints' twists [Marinho *et al.* 2016]. For this reason, the development of strength in both upper and lower limbs is important to achieve success during combat.

On the other hand, in combat sports, it is of major importance to know the body composition of the athletes in order to evaluate and control the weight category in which athletes will participate. For this reason, studies to evaluate this aspect are necessary Monterrosa *et al.* [2022]. However, the results reported in the literature exhibit large variations Andreato *et al* [2017]. Thus, update reference values for some anthropometric measurements and somatotypes in elite BJJ athletes are necessary today.

In grappling sports such as BJJ, wrestling and judo, the somatotype (especially the mesomorphic one) is an important factor in athletes' performance [Franchini *et al.* 2011; Andreato *et al.* 2017], since it serves as a physical level measurement [Ramirez-Velez *et al.* 2014]. Body composition has a direct relationship with physical performance and represents a strong influence for victory in combat sports. Thus, athletes with a high percentage of muscle mass will have greater chances of success in the confrontations [Monterrosa *et al.* 2019].

Besides an adequate body composition, BJJ requires various physical attributes such as muscle power and postural balance [Jungman, Wilson 2016; Olavo de Paula Lima *et al.* 2017]. In this regard, biomechanical factors such as plantar pressure are very important and have a decisive role in increasing speed and stability, due to the pressure exerted by the foot on the ground [Teodoru, Razvan 2014]. Plantar pressure assessment can provide information about plantar loading characteristics during different functional activities. Moreover, it would be of special interest for coaches and physical trainers to be able to evaluate plantar pressure parameters of their athletes, in order to design training focusing on the prevention of lower limb injuries and body imbalances [Wong *et al.* 2007]. However, there is a lack of studies evaluating these baropodometric parameters in BJJ athletes.

Considering the previous information, and since Brazilian Jiu-Jitsu is not a sport extensively studied concerning anthropometric aspects, lower limbs performance and postural balance, the purposes of this study were three-fold: (i) to describe anthropometric and morphological characteristics of elite BJJ athletes; (ii) to evaluate lower limbs asymmetry and (iii) to present reference values for different baropodometric parameters in BJJ athletes.

Materials and methods

<u>*Design and Participants*</u>

A total of 16 elite male BJJ athletes (brown and black belts) were recruited for this cross-sectional observational and non-probabilistic study (32.2 ±4.5 years; weight 80.2 ± 9.7 kg; height 180±0.05 cm and 6.3 ± 3 years of training experience). The subjects were recruited from various sports academies of the state of Santa Catarina (Brazil), with the support of several coaches.

The prerequisites to participate in this study were the followings:

I. Be a competitor/athlete with national or international experience.

II. Be exempt from any injury.

III. Be currently training with a frequency of at least 5 days of training a week.

IV. Be a *right-leg dominant* athlete.

Participants presenting altered foot arch (i.e. excessive fallen arch or high arch) were not included in this study because of the influence on foot pressure distribution. For example, individuals with flat feet have been shown to have decreased maximum force in the middle forefoot [Queen *et al.* 2009].

The approval of the ethics committee in human procedures was obtained from the Federal University of Santa Catarina in accordance with the Declaration of Helsinki.

Procedures and measures

Participants were instructed to refrain to train for 24 h before data collection. Subsequently, data were collected the same day in the biomechanics laboratory of the Federal University of Santa Catarina, during the preparatory stage (pre-season) in the morning hours (8:00–11:00 a.m.), in fasting conditions. Evaluations were conducted in the following order: anthropometry, countermovement jump and finally the baropodometric assessment.

Anthropometry

All variables were taken by a level-2 anthropometrist, in accordance with the international standards for anthropometric assessment published by the International Society for the Advancement of Kinanthropometry – ISAK. For data analysis, averages of two measurements of each anthropometric variable were calculated and processed. To reduce the technical error of measurement, measurements were taken in triplicate if the difference between the first and second measurements was greater than 5% for skinfolds and 1% for the other measurements.

Body weight was measured using an electronic scale (SWAN, Pekin, China) and was rounded to the nearest 0.1 kg. Height was measured using a stadiometer (CESCORF, Porto Alegre, Brazil) and rounded to the nearest 0.5 cm. Circumference was measured for flexed arm, relaxed arm, forearm, thigh, calf, waist, and hip with a constant-tension steel tape (CESCORF, Porto Alegre, Brazil). Breadths were measured for humerus and femur segments with special equipment (Body Trends, Carpinteria, CA). Skinfold-thickness was measured for biceps, triceps, subscapular, suprailic, supraspinal, abdomen, anterior thigh, and medial calf regions on the right side of the body with the skinfold caliper (CESCORF, Porto Alegre, Brazil).

Morphology and body composition

To perform the morphological characterization, we analyzed the raw data obtained for each anthropometric variable (skinfolds, breadths and girths) and calculate the skinfold-corrected muscle girths. Then, these body regions were used to estimate body fat (%) by Withers' equation [Withers *et al.* 1987] and somatotype by the Heath-Carter anthropometric somatotype method [Heath and Carter. 1967]. From these measurements, we estimated waist/hip ratio, waist/height ratio (m), anatomical cross-sectional area (cm^2), body adiposity index (%), fat mass (kg), fat free mass (kg), fat max index ($kg^* m^2$), fat free mass index ($kg^* m^2$) and the reciprocal ponderal index ($cm.kg^{-1/3}$) were estimated according to the following formulas presented in **Table 1**.

Body proportionality

Body proportionality analyses were conducted using the Phantom stratagem proposed by Ross and Wilson [1974]. This method is used to describe individual anthropometric characteristics as belonging to a metaphorical model: a particular number of z-scores away from the mean phantom.

The Phantom stratagem is an asexual and arbitrary human reference model for body proportionality with specific anthropometric characteristics derived from male and female reference data [Ross, Wilson 1974]. Each variable was adjusted to the Phantom size using the equation:

$$Zscore=V[(170.18/h)^{d} - p]/s;$$

where "V" is the value obtained from the variable studied, "170.18" is the constant of proportionality for height in the Phantom model, "h" is the subject's height, "d" is a dimensional exponent, "p" is the Phantom mean value for variable "V", and "s" is the Standard deviation for variable studied in the Phantom model.

Vertical jump and bilateral asymmetry index assessment

Vertical jump performance was assessed using an electronic force platform (Quattro Jump, Kistler, Switzerland) with a sampling frequency of 500 Hz. Subjects were then allowed up to three sub-maximal trials to practice the technique. Once the submaximal trials were completed, the athletes performed each assessment. Counter Movement Jump (CMJ) was performed in a randomized way, bilaterally. Athletes performed a CMJ according to the protocol described by Impellizerri *et al.* [2007]. Before testing, athletes performed a warm-up, which included

Table 1. Formulas to estimate anthropometric indices and body composition

AIS	Formulas	Reference
WHR	Waist (cm) / hip (cm)	NR
WHTR	Waist (cm) / height (cm)	NR
BADI	[hip circumference (cm)/ height(m)$^{1.5}$]-18	[Bergman *et al.* 2011]
BMI	Body weight (kg)/ height (m)^2	[Keys *et al.* 2014]
CSA	$0.649 \times (TG/\pi - TSF)^2 - (0.3\times TB)^2$	[Knapik *et al.* 1996]
FM	(BF%/100) × body weight (kg)	[Eckhardt *et al.* 2003]
D	D = 1.0988 – (0.0004 x TR + SB + BI + SE + AB + FT + CH)	[Withers *et al.* 1987]
BF (%)	BF% = (4.95/D) -4.5 x 100	[Siri 1961]
FFM	BW (kg)-FM (kg)	[Eckhardt *et al.* 2003]
FMI	FM (kg) / height (m)^2	[Eckhardt *et al.*2003]
FFMI	FFM (kg)/height (m)^2	[Eckhardt *et al.* 2003]
RPI	height (cm)/ weight (kg)$^{1/3}$	[Khosla 1967]
MMUL	$(((H - TPS) x (0,043 \times (UARG)^2))–bw) / 1000$	[Rodriguez *et al.* 2010]
MMLL	$(((H - \Sigma TCP) \times (TB)^2) + (GT + CG)) /1000$	[Rodriguez *et al.* 2010]
TBSM	$Ht \times (0.00744 \times CAG^2 + 0.00088 \times CTG^2) + (0.00441 \times CCG^2) + 2.4 (sex – 0.048 \times age) + race + 7.8$	[Lee *et al.* 2000]

AIS, anthropometric indicators; WHR, waist to hip ratio; WHTR, waist to height ratio; BADI, body adiposity index; BMI, body mass index; CSA, anatomical cross-sectional area; TG, thigh girth; TSF, thigh skinfold; TB, thigh breadth; CSA, cross-sectional area; D: Density; TR, triceps; SB, subscapular; BI, biceps; SE, supraspinal; AB, abdominal; FT, front thigh; CH, chest; %BF: Body Fat percentage; FM, fat mass; FFM, fat free mass; FMI, fat mass index; FFMI, fat free mass index; RPI, reciprocal ponderal index; MMUL, muscle mass of upper limbs; H, height; TPS, tricipital skinfold; UARG, Upper arm relaxed girth; BW, body weight; MMLL, muscle mass of lower limbs; ΣTCS, thigh and calf skinfold sum; TB, thigh breadth; TG, thigh girth; CG, calf girth; TBSM, Total-body skeletal muscle mass; CAG, corrected arm girth (cm); CTG, corrected thigh girth (cm); CCG, corrected calf girth (cm); NR, no reference.

five minutes of light running, skipping and dynamic exercises like half squats, lunges and leg swings. After that, they performed self-administered submaximal CMJ trials to practice the technique (5 repetitions). Verbal motivation and encouragement were given to maximize the effort. All jumps were performed with hands kept on hips to prevent any influence of arm movements on the vertical jumps and to avoid coordination as a confounding variable in the assessment of the leg extensors neuromuscular performance [Chaouachi *et al.* 2009].

Each subject performed 5 maximal CMJs with two minutes of passive rest between each attempt. Athletes were asked to jump as high as possible, and the value of the highest jump was used for analysis.

To assess unilateral performance by CMJ, subjects placed one leg on the force platform and the contralateral leg on a wooden base at the same level **(Fig.1)**.

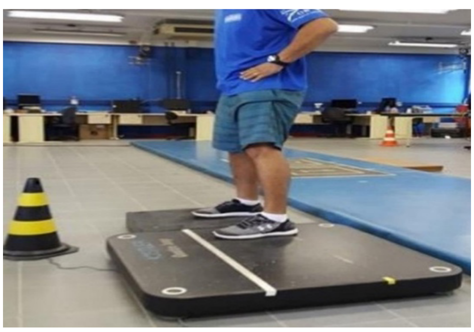


Figure 1. Procedure to assess unilateral performance using force platforms BAI* was quantified using the equation proposed by Impellizzeri *et al.* [2007]: **BAI**
* Bilateral Asymmetry Index

Plantar assessment
All subjects conducted an electronic baropodometry test, in static conditions without footwear. We used the electronic platform MobileMat (Matscan, Tekscan, Inc., Boston, USA) with a sampling frequency of 100 Hz and 8,448 electronic sensors covered by a captor that gives pressure information from each foot to an electronic elaborator. Data were processed using the FootMat Research 7.10. software. During measurement, subjects stood on the platform in an orthostatic position with the arms pending along the body with their eyes open, looking at a reference point located 3 meters away, on the wall of the examination room for 60 seconds, with an interval of 30 seconds between each attempt. All subjects were evaluated in the same baropodometer. The following parameters were considered on both feet: the percentage of distribution of load between rearfoot and forefoot, peak power, maximum force right, peak pressure, mean peak pressure variable. With the data collected, the asymmetry index equation in the plantar regions was applied.

The forefoot was assumed as the foot part anterior to the gravity center and the rearfoot as the part posterior to the gravity center registered on the device **(Fig. 2).**

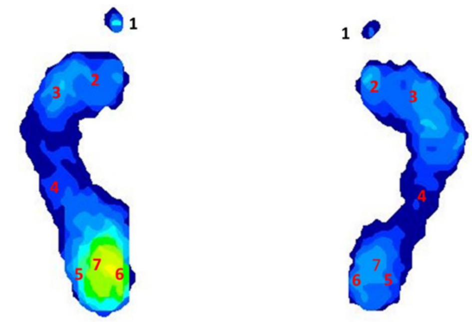


Figure 2. Foot outline with eight regions of interest that to evaluate foot loading characteristics. 1: Hallux; 2: Central forefoot; 3: Lateral forefoot; 4: Midfoot; 5: Lateral heel; 6: Medial heel; 7: Central heel.

Figure 2. Foot outline with eight regions of interest to evaluate foot loading characteristics. 1: Hallux; 2: Central forefoot; 3: Lateral forefoot; 4: Midfoot; 5: Lateral heel; 6: Medial heel; 7: Central heel.

Statistical analysis

Descriptive and exploratory statistics were performed in SPSS 25.0 (SPSS/IBM, Chicago, IL, USA) for the different parameters analyzed. The proportionality of body mass fractionation was determined with the Phantom Z-score stratagem using Microsoft Excel 2016. We calculated a Pearson's correlation when data followed a normal distribution. The alpha level was set to 0.05. The normality of distribution was checked with the Shapiro-Wilk test.

Likewise, when we compared baropodometric parameters between right and left foots, we used a two-tailed paired Student's t test and two-tailed Student's t-test. Data were expressed as mean ± standard deviation, range and confidence intervals (95%).

Results

BJJ requires high levels of muscular strength in both upper and lower limbs to perform different short and high-intensity actions such as strangles and grappling [Spanias *et al.* 2019]. **Tables 2** and **3** provide descriptive results for anthropometric characteristics and body proportionality scores for the elite BJJ. No differences were found between the left and right sides anthropometric measures (data not shown). Athletes in the present study had a balanced mesomorph somatotype (2.2-6.2-1.6), ranging from 1.4–3.2 for endomorphy, 4.4–8.3 for mesomorphy and 0.1–3.5 for ectomorphy. To ease the interpretation of the somatotype results, a graphical description of individual values is shown in **figure 3**.

Regarding proportionality, BJJ showed a higher upper body girth Z-score (Upper arm relaxed 3.1±1.3 and upper arm tensed 3.1±1.2), and reduced lower body girth Z-score (Right thigh -0.3±0.9, Left thigh -0.2±0.7, Right calf 0.3±0.7 and Left calf 0.1±0.7) compared to the phantom model.

Table 2. Morphological characteristics of BJJ athletes.

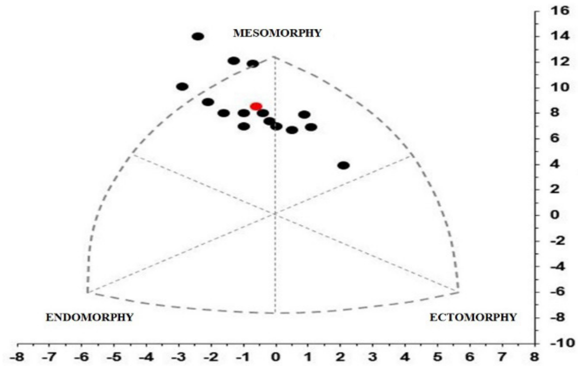
	Mean ± SD	Range	95% CI	
Breadth (cm)				
Humerus	7.2±0.4	6.4 to 7.7	6.9	7.4
Rigth femur	9.8±0.4	9.3 to 10.6	9.4	9.9
Left femur	9.6±0.3	9 to 10	9.6	10
Girth (cm)				
Upper arm relaxed	35.3±2.8	29.3 to 39.6	33.8	36.8
Upper arm tensed	38±2.4	33 to 41.7	36.7	39.3
Right thigh	56.4±3.8	50.8 to 64	54.3	58.4
Left thigh	56.7±3.3	52.6 to 63	54.9	58.5
Right calf	37.2±2.0	34.3 to 41	36.2	38.3
Left calf	36.8±1.9	33.5 to 40	35.7	37.8
Waist	84.6±6.1	76.1 to 95.2	81.4	87.9
Hip	97.6±5.4	88.1 to 107.8	94.7	100.5
Skinfolds (mm)				
Biceps	2.7±0.8	2 to 5	2.3	3.1
Triceps	5.7±1.4	3 to 8	5	6.5
Subscapular	10.4±2.6	6.8 to 15	9	11.8
Suprailiac	12.4±5.1	6.5 to 25	9.7	15.1
Supraspinal	7.4±2.8	4 to14	5.9	8.9
Abdominal	15.0±4.7	7 to 24.5	12.5	17.5
Right thigh	11.8±3.5	7 to 17.5	9.5	13.2
Left high	11.0±2.9	6 to 15	9.5	12.5
Right calf	6.7±2.3	4 to 13	5.5	7.9
Left calf	6.4±2.1	4 to 13	5.3	7.6
Somatotype				
Endomorphy	2.2 ± 0.6	1.4 to 3.2	1.9	2.6
Mesomorphy	6.2 ± 1.0	4.4 to 8.3	5.7	6.8
Ectomorphy	1.6 ± 0.9	0.1 to 3.5	1.1	2

Table 3. Z-score values of the phantom method for morphological characteristics in BJJ athletes.

	Mean ± SD	Range	95% CI	
Breadth (cm)				
Humerus	1.2±1.0	-0.5 to 2.4	0.7	1.8
Right femur	-0.2±0.8	-1.6 to 1.2	-0.6	0.3
Left femur	-0.5±0.5	-1.2 to 0.5	-0.7	-0.2
Girth (cm)				
Upper arm relaxed	3.1±1.3	0.2 to 5	2.4	3.8
Upper arm tensed	3.1±1.2	0.5 to 4.8	2.5	3.7
Right thigh	-0.3±0.9	-1.6 to 1.4	-0.2	-0.8
Left thigh	-0.2±0.7	-1.4 to 1.10	-0.6	0.1
Right calf	0.3±0.7	-0.9 to 1.8	-0.1	0.7
Left calf	0.1±0.7	-1.0 to 1.4	-0.3	0.5
Waist	2.2±1.4	-0.3 to 4.4	1.4	3.0
Hip	-0.1±0.9	-1.6 to 1.9	-0.5	0.4
Skinfolds (mm)				
Biceps	-2.7±0.4	-3.1 to -1.5	-2.9	-2.5
Triceps	-2.2±0.3	-2.8 to -1.8	-2.4	-2.0
Subscapular	-1.4±0.5	-2.10 to -0.4	-1.7	-1.1
Suprailiac	-1.5±0.7	-2.4 to 0.3	-1.9	-1.1
Supraspinal	-1.8±0.6	-2.5 to -0.4	-2.2	-1.5
Abdominal	-1.4±0.6	-2.4 to -0.1	-1.7	-1.1
Right thigh	-1.9±0.4	-2.5 to -1.2	-2.2	-1.7
Left high	-2.0±0.3	-2.6 to -1.5	-2.1	-1.8
Right calf	-2.0±0.5	-2.6 to -0.7	-2.3	-1.8
Left calf	-2.1±0.5	-2.6 to -0.7	-2.3	-1.8

Body composition is an important performance variable in BJJ athletes. In BJJ competitions, athletes are divided according to body weight. A greater percentage of muscle mass, lower BF% and mesomorph somatotype are associated with competitive success [Andreato *et al.* 2017]. Thus, maintaining a lean physique is important for the fighters [Jones, Ledford 2012]. **Table 4** provides descriptive results of the analysis carried out on body composition and different body indices. Athletes in the present study had a mean BF % of 10.5 and 33.7 kg of total body skeletal mass.

Figure 3. Somatotype distribution (somatochart) of elite BJJ athletes.



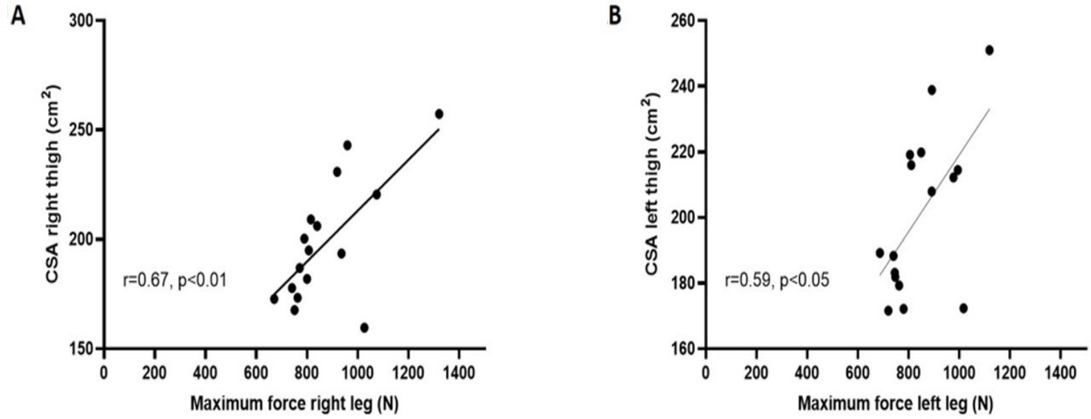
In order to evaluate potential relationships between anthropometric variables and physical performance in lower limbs, analyses were performed using Pearson correlation. Analysis revealed positive associations solely between estimated cross-sectional area in both right and left thigh and maximum force in right and left legs respectively, during unilateral vertical jump ($r=0.67$, $p<0.01$ and $r=0.59$, $p<0.05$ respectively) as shown **figure 4.**

Table 4. Body composition and anthropometric indices of elite BJJ.

	Mean ± SD	Range	95% CI	
Variable				
FM (kg)	8.4 ± 2.0	5.6 to 13.6	7.3	9.5
FFM (kg)	71.7 ± 8.8	59.4 to 90.4	67	76.4
FMI (kg. m−2)	2.7 ± 0.7	1.7 to 4.5	2.3	3.1
FFMI (kg. m−2)	23.0 ± 2.3	20.1 to 28.8	21.8	24.3
BMI (Kg. m^{-1})	25.8 ± 2.7	21.8 to 31.9	24.3	27.2
Σ6 skinfolds (mm)	56.7 ± 12.2	40.5 to 82.5	50.2	63.2
Σ8 skinfolds (mm)	71.8 ± 17.9	49.5 to 110	62.7	80.9
Body fat %	10.5 ± 2.2	7.6 to 14.9	9.3	11.6
Total body skeletal mass (kg)	33.7 ± 3.4	28 to 39.8	31.9	35.6
Muscle mass in upper limbs (kg)	9.1 ± 1.4	6.5 to 11.7	8.3	9.9
Muscle mass in lower limbs (kg)	15.2 ± 1.7	13.3 to 18.9	14.3	16.1
WHTR (m)	0.5 ± 0.0	0.4 to 0.5	0.5	0.5
WHR	0.87 ± 0.0	0.8 to 0.9	0.8	0.9
RPI (cm. kg^{-1})	41.0 ± 1.4	38.2 to 43.8	40.3	41.8
BADI	23.7 ± 2.3	20.1 to 29	22.5	25
CSA Right thigh (cm^2)	198.4 ± 28.0	159.7 to 257.3	183.6	213.4
CSA Left thigh (cm^2)	201.1 ± 24.7	171.6 to 251	187.9	214.2

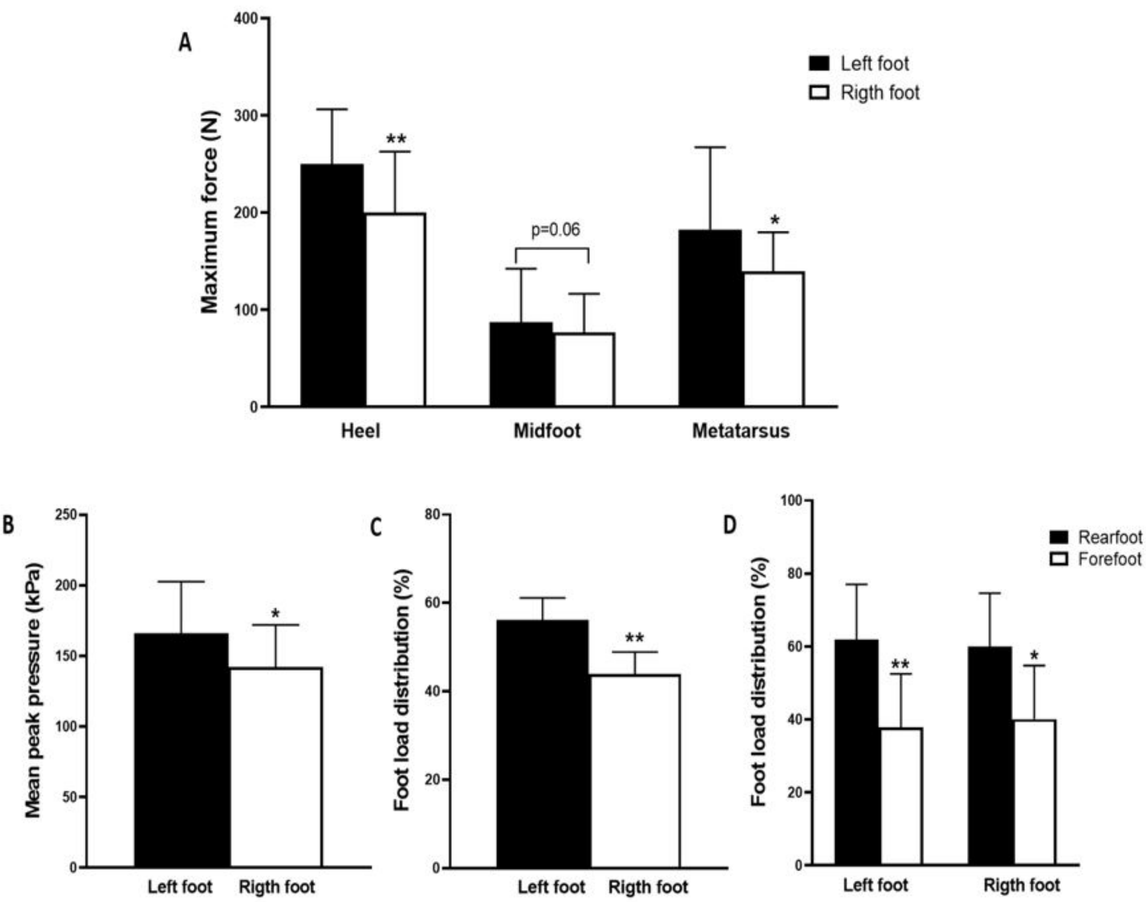
FM, fat mass; FFM, fat free mass; FMI, fat mass index; FFMI, fat free mass index; BMI, body mass index; Σ6 skinfolds, sum of the six *skinfolds (triceps, subscapular, supraspinal, abdomen, thigh and calf)*; Σ8 skinfolds *(triceps, subscapular, supraspinal, abdomen, thigh, calf, biceps and suprailiac)*; WHTR, waist to height ratio; WHR, waist to hip ratio; RPI, reciprocal ponderal index; BADI, body adiposity index; CSA, cross-sectional area.

Figure 4. Bivariate correlations between anthropometric and physical performance parameters



Pearson's correlation test between CSA thigh and maximum force in right leg **(A)** and left leg **(B)**. for both, values inside the graph indicate the p value of the correlation.

Figure 5. Baropodometric analyzes in elite Brazilian Jiu-Jitsu athletes.



(A) Maximum force in the heel, midfoot and metatarsus (B) Mean peak pressure between left and right foot (C) Percentage of foot load distribution between left and right foot and (D) Percentage of load distribution on left and right feet. Bars represent Mean ± SD. Statistical significance was assessed using a 2-tailed paired Student's t test and two-tailed Student's t-test. **p<0.01, * p<0.05.

In BJJ, the main goal is the submission of the opponent through the application of a stranglehold or joint locks, The need for different forms of strength in BJJ has been documented previously [Ferreira Marinho *et al.* 2016]. CMJ is mostly used test for coaches to evaluate lower limb muscle strength, due to the simplicity and richness of outcome information [Markovic *et al.* 2004]. Jump height and peak power/weight are useful variables to describe explosive leg muscles.

Table 5 shows results in vertical jump performance and baropodometric assessment in static conditions (percentage plantar load values, maximum force, peak pressure and mean peak pressure) in BJJ. Overall, descriptive analyses showed that our athletes jumped

~42cm with a relative peak force and relative peak power of ~22 $N.kg^{-1}$ and ~45 $W.kg^{-1}$, respectively. On the other hand, when we analyzed the results of baropodometric parameters, we found significant differences in foot load distribution percentage between the left and right feet (56.1 ± 5.0 vs 43.9 ± 5.0, respectively) and between rearfoot and forefoot in the left foot (61.9 ± 15.1 vs 37.9 ± 14.6, respectively).

Table 5. CMJ performance and Baropodometric parameters in BJJ athletes.

Vertical jump performance	Mean ± SD	Range	95% CI	
Jump height (cm)	41.9 ± 4.7	33.7 to 50.2	39.4	44.5
Maximum force$_{both}$ (N.)	1713.4 ± 272	1393 to 2392	1568	1858.7
Maximum force$_{both}$ ($N.kg^{-1}$)	21.4 ± 2.1	18 to 24.8	20.3	22.5
Maximum force right leg (N.)	874.1 ± 162.3	671 to 1321	787.6	960.5
Maximum force left leg (N.)	845.9 ± 124.9	686.3 to 1119	779.4	912.5
Maximum force right leg ($N.kg^{1}$)	10.9 ± 1.5	8.7 to 15	10.1	11.7
Maximum force left leg ($N.kg^{1}$)	10.6 ± 1.4	8.6 to 14.8	9.8	11.4
Peak power$_{both}$ ($W.kg^{1}$)	45.3 ± 4.8	38.6 to 56.3	42.7	47.9
Peak velocity$_{both}$ ($m.s^{1}$)	2.6 ± 0.1	2.3 to 2.9	2.5	2.7
BAI (bilateral asymmetry index, %)	6.3 ± 4.3	0.7 to 15.3	4.0	8.6
Foot load distribution foot (%) #				
Left foot %	56.1 ± 5.0	48 to 67	53.5	58.8
Right foot %	43.9 ± 5.0**	33 to 52	41.2	46.5
Left forefoot %	37.9 ± 14.6$$	18 to 73	30.2	45.7
Left rearfoot %	61.9 ± 15.1	24 to 82	53.8	69.9
Right forefoot %	40.1 ± 14.7$	21 to 69	32.3	47.9
Right rearfoot %	59.9 ± 14.7	31 to 79	52	67.7
Maximun force and peak pressure on feet#				
Maximun force left heel (N)	250.1± 56.6	141.6 to 335.7	219.9	280.3
Maximun force right heel (N)	200.2 ± 63**	51.5 to 289.6	166.7	233.8
Maximun force right midfoot (N)	76.9 ± 39.8	14.7 to 191.4	55.7	98.2
Maximun force left midfoot (N)	88.2 ± 54.1	26.8 to 235.9	59.3	117
Maximun force right metatarsal (N)	139.7 ±40.3**	73.7 to 202.2	118.2	161.1
Maximun force left metatarsal (N)	182.8 ± 84.7	54.3 to 341.8	137.7	227.9
Peak pressure left foot (kPa)	198 ± 58.8	125 to 349	167.1	229.7
Peak pressure right foot (kPa)	175 ± 49.4	103 to 313	149.6	202.2
Mean peak pressure left foot (kPa)	166 ± 36.6	119 to 235	146.6	185.6
Mean peak pressure right foot (kPa)	142 ± 30.0*	94 to 213	126	158

#Baropodometric parameters of forefoot and rearfoot in static conditions (standing); $p<0.05 vs right rearfoot; $$p<0.01 vs left rearfoot; *p<0.05 vs left foot; ** p<0.01 vs left foot.

In addition, the analysis revealed greater levels of maximum force in both metatarsus and heel in the left foot, than those in the right foot (182.8 ± 84.7 N vs 139.7 ± 40.3 N and 250.1± 56.6 N vs 200.2 ± 63 N, respectively). Finally, Mean peak pressure was greater in the left foot than the right foot (166 ± 36.6 vs 142 ± 30.0 kPa, respectively). T-test plots are shown in **figure 5**.

Discussion

In this study, we provide an overview of morphological characteristics in BJJ and describe different performance variables related to vertical jump performance and baropodometric measures. Among the main findings, significant differences ($p < 0.05$) were found in baropodometric measures between feet, and when we compared the rearfoot and forefoot surfaces in both the left and right foot.

Somatotype and body composition

Many studies have negatively associated body fat and body composition with performance in combat sports [Marinho *et al.* 2016]. It has been demonstrated that a mesomorphic profile in athletes could be an important factor in achieving success during a fight [Baez *et al.* 2014; Ovretveit 2018]. In combat sports, the mesomorphic component has been highlighted as the most relevant for performance and for discriminating athletes of different levels [Franchini *et al.* 2011]. To our knowledge, only four studies have determined the somatotype in BJJ athletes [Andreato *et al.* 2017]. However, in all of them, the mesomorph component was the predominant one. Our results are consistent with these reports, as we found a *balanced mesomorph somatotype* indicating a strong development of muscle mass and bone structure which are required to guarantee defensive actions [Pietraszewska *et al.* 2014; Andreato *et al.* 2017]. These results support the idea that high rates of mesomorphism are typical of elite athletes, demonstrating strong musculoskeletal development.

Regarding body composition, athletes in the present study had a mean BF of 10.5%, which can be considered as lean. Our results are consistent with those reported by Andreato *et al* [2017] in elite BJJ athletes (BF of 10.3%), by using the same equation as we did. Although other studies reported results from 7.1% to 15.7% in elite male BJJ athletes, different skinfold-based equations were used [Andreato *et al.* 2017]. Thus, our results demonstrate that low BF% is characteristic of elite BJJ athletes.

It is noteworthy that variation of BF% results reported in the literature could be due to factors such as the time of the season in which the measurements were taken, as well as the equations selected to estimate the variables. In this sense, this divergence makes it difficult to compare our results with other studies. For instance, by using the Jackson and Pollock equation, in high-level BJJ athletes, Da silva *et al* [2015] and Andreato *et al* [2015] reported almost 100% variation between their results (BF% of ~7.4 and ~13 respectively). For that reason, in order to make more accurate comparisons between studies when performing body composition analysis, we suggest considering the variable "skinfold summation" in addition to body fat percentage.

In the same way, estimation of other variables and indices related to body composition is of great importance because it provides more information about the physical structure of the athletes. Because there are many methods for body composition estimation, comparing the results between studies is difficult. In our study, we found that total body skeletal mass, BMI, FFM, FFMI, BADI and RPI indices were similar to those reported in the literature for BJJ [Baez *et al.* 2014; Pietraszewska *et al.* 2014; Detanico *et al.* 2020; Andreato et al. 2017] wrestlers [Ramirez-Velez *et al.* 2014] and Greco-Roman wrestlers [Sterkowicz-Przybycien, Sterkowicz and Zarów, 2011]. Thus, our results provide useful reference values to be compared with futures studies.

Proportionality

Body proportionality has been shown to be related to success in different sports [Gutnik *et al.* 2015]. Upper-limb muscle strength is one of the most important physical capacity for high performance in BJJ [Soares *et al.* 2005] because most techniques require grappling. Upper-arm composition received considerable attention during the last few decades in body composition and nutritional status fields. Mid-upper arm circumference and triceps skinfold thickness are used extensively [Rolland-Cachera *et al.* 1997]. In our study, athletes showed higher Z-scores in upper-limb girths than both, lower limbs and the phantom model, suggesting a regional distribution of muscle mass. Likewise, representative areas of adipose tissue such as the abdominal region, and the 8 skinfolds used to quantify body fat, showed lower proportionality than the reference variable of the phantom stratagem, similar to that reported in the literature [Baez *et al.* 2014].

Lower limbs performance

Vertical jump performance is considered a good indicator of muscle power in the lower limbs. [Markovic *et al.* 2004; Kons *et al.* 2017]. Previous research showed that elite BJJ have greater lower limb strength than their novice counterparts, indicating the importance to train this physical performance variable [Andreato *et al.* 2017]. CMJ is a reliable and largely used *tool* to measure *lower-limb* power capacity [Markovic *et al.* 2004], and it is also the most largely used in combat sports [Da Silva *et al.* 2014; Kons *et al.* 2017; James *et al.* 2020]. Because both offensive and defensive techniques including guard pass, sweeps, submissions and takedowns require high muscular strength and power in the lower limbs, force produced during the CMJ test is a relevant measure in BJJ.

Some evidence indicates that in combat sports, including BJJ, height reached between 30 to 48 cm in the CMJ test [Ramirez-Velez *et al.* 2014; Diaz-Lara *et al.* 2015; Andreato *et al.* 2017; Spanias *et al.* 2019; Follmer *et al.* 2021]. In BJJ, the continuous movements across the mat to attain an advantageous position over the opponent, and determinant techniques such as triangle chokes, guard passes, takedowns, submissions, etc., require high levels of muscle power in the lower limbs [Diaz-Lara *et al.* 2015]. Here, we have found a mean of ~42cm in CMJ test in elite jiu-jitsu athletes with relative maximum force, relative peak power and peak velocity of ~21 N. Kg^{-1}, 45,3 $W.kg^{-1}$ and 2,6 m. s^{1} respectively. As such, the present study exhibits consistency with previous findings [Da Silva *et al.* 2014; Andreato *et al.* 2015; Diaz-Lara *et al.* 2016; Kons *et al.* 2017]. In this sense, our results demonstrated that athletes in this study presented important levels of strength and power in the lower extremities and can be used as reference values in this population.

In addition, Pearson correlation analyses revealed a positive association between maximum force in both the right and left leg in CMJ and CSA in both right and left thigh ($r = 0.67$, $p<0.01$ and $r = 0,59$, $p<0.05$ respectively), which could indicate a relationship between the unilateral muscle mass and the maximum force applied during unilateral CMJ. However, future studies should determine the relationship between different anthropometric variables and lower limb physical performance in BJJ athletes.

On the other hand, asymmetrical strength in lower extremities has been defined as "the inability to produce a force of contraction that is equal across the quadriceps and hamstring of both the right and left sides" [David *et al.* 2011]. Thus, assessing asymmetry in lower limbs may provide insights into injury risk and physical performance[Manning, Pickup 1998; Ojeda-aravena *et al.* 2021].

Lower limb asymmetry values greater than 10% or 15% have been reported as deleterious for physical performance and increased risk of injury. However, there is evidence indicating no relationship between strength asymmetries and injury or performance [Bennell 1998; Sean 2019]. To the best of our knowledge, only one study assessed lower limb asymmetry in BJJ practitioners, including female and male athletes, which reported asymmetry values of 7.7% and 12.1% respectively [Detanico *et al.* 2020]. Our findings indicate lower asymmetry levels (6.3%) than those reported by Detanico's group. This could be due, at least partially, to differences in variables such as age, years of training experience, weekly training frequency and the level of athletes (i.e. local, national or international experience). Thus, elite BJJ athletes could present lower asymmetry in the lower extremities than their novice counterparts, but this gap has not been studied yet.

Baropodometric assessment

Baropodometry is a technique to measure the distribution of static plantar pressure by providing data on peak pressure on specific foot areas [Oliveira *et al.* 2017] and to analyze the effects of different factors such as body weight, post-surgery processes or asymmetries on foot morphology.

Physical training alters locomotion patterns and baropodometric parameters, which might be at higher risk of a stress injury in the foot. There is evidence of different variations of plantar support in subjects according to sport [Feka *et al.* 2019]. Balance is an important physical attribute in combat sports such as BJJ to maintain a good defense. During combat, athletes need to maintain posture control to resist going down.

To the best of our knowledge, no research reported baropodometric parameters – i.e load distribution foot, peak pressure, mean peak pressure and maximum force in different foot regions in BJJ. Previously, we have presented preliminary results of the present investigation by comparing Muay Thai and BJJ athletes [Monterrosa, Moro 2020]. However, our present research provides a more extensive descriptive analysis. Here we wondered whether high-performance BJJ practice could alter foot support patterns between feet. Interestingly, statistical analyses showed asymmetric heels, midfoot (trend only) and metatarsal maximum forces, mean plantar pressure peak and load distribution with higher measurements on the left foot (**fig**. **5A, B** and **C**). In this study, all athletes were right-leg dominant. Thus, higher values in baropodometric parameters in non-*dominant leg* could be due to a greater predisposition of the left foot to work in defensive situations which require balance.

Here, it is plausible that the dominant side of our athletes could be more predisposed to attack situations such as leg lock, scraping or triangle choke. We believe that the asymmetries found in the different baropodometric parameters in this study should not be a cause for concern among coaches. Thus, these asymmetries would not be a sign of injury risk, but rather of the nature of the sport itself.

In addition, differences were observed between rearfoot and forefoot in foot load distribution in both feet **(fig. 5D)**. Athletes showed a higher load distribution percentage in the rearfoot than the forefoot surface in both the left (61.9% and 37.9%, respectively) and right foot (59.9% and 40.1% respectively). Our findings do not agree with those previously reported in soccer players and judokas [Feka *et al.* 2019]. Thus, we believe that this characteristic in plantar support is due to the specificity of BJJ. It is possible that a greater distribution of the load on the rearfoot could generate greater stability in most situations during combat in decisive techniques (movements across the mat, guard passes, takedowns, submissions). However, more studies are needed to corroborate this hypothesis.

Conclusions

The main purpose of our study was to provide insight into anthropometric, physical performance and baropodometric parameters that might affect BJJ performance. We found that body composition, somatotype and proportionality in elite BJJ athletes were similar to that reported in studies with combat sports athletes. Thus, our study contributes to increasing knowledge about this aspect.

On the other hand, the findings of the present study related to physical performance and lower limb asymmetry provide a profile of elite BJJ athletes, demonstrating that high levels of strength and power along with low percentages of asymmetry are characteristic of top-level athletes. These data facilitate useful reference values for determining training priorities.

Finally, the results of this study provide novel information on the baropodometric parameters of elite BJJ athletes and show that the non-dominant leg may have a predisposition to work in defensive situations that require balance, exerting greater support on the rearfoot than on the forefoot. Future studies observing different women athletes and different competitive levels will further enhance our knowledge regarding baropodometric profile of BJJ athletes and the relationships between this variable and physical performance.

Limitations of the study

Some limitations are inherent in the present study. First, the sample of volunteers was limited and may have introduced bias. However, our subjects are valuable as avowed elite athletes. Secondly, our measurements are cross-sectional and therefore we cannot discard some undetected bias. We would like to mention that there are no cross-sectional or longitudinal studies that performed baropodometric analysis in elite BJJ. Finally, we have not been able to include female athletes in our study. *Further research* is needed to analyze baropodometric parameters in women and novice BJJ practitioners in both dynamic and static conditions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

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Ethics declarations

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. All authors read and approved the final manuscript.

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Morfologia, wydolność kończyn dolnych i charakterystyka baropodometryczna elitarnych zawodników brazylijskiego *Jiu-jitsu*

Słowa kluczowe: podparcie stopy, charakterystyka antropometryczna, somatotyp, wysoka sprawność

Streszczenie
Wprowadzenie. Zawodnicy brazylijskiego *jiu-jitsu* (BJJ) charakteryzują się mezomorficznym somatotypem i wymagają dużej siły i mocy mięśniowej w kończynach dolnych w celu wykonywania potężnych działań ofensywnych i defensywnych podczas walki. Ponadto zarówno nacisk, jak i podparcie plantacyjne są bardzo ważne i mają decydującą rolę w zwiększeniu szybkości i stabilności podczas walki.
Problem i cel. Określenie cech morfologicznych i baropodometrycznych elitarnych zawodników BJJ.
Metody. U 16 elitarnych BJJ wykonano następujący test: skład ciała, jednostronny i dwustronny skok z kontry oraz ocenę baropodometryczną w warunkach statycznych.
Wyniki. Zawodnicy prezentowali niski procent tkanki tłuszczowej (10,5 ± 2,2%) i zrównoważony mezomorficzny somatotyp (2,2- 6,2-1,6). W zakresie sprawności siłowej kończyn dolnych zaobserwowano odpowiednio: 41,9 ± 4,7 cm, 1713,4 ± 272 N oraz 6,3 ± 4,3% wysokości skoku pionowego, siłę maksymalną i niski procentowy wskaźnik asymetrii obustronnej. Dodatkowo analiza baropodometryczna wykazała wyższe wartości siły maksymalnej w strefie pięty i śródstopia ($p<0,05$), w szczycie nacisku i rozkładzie obciążenia w stopie niedominującej ($p<0,05$). Ponadto zaobserwowano większy procentowy rozkład obciążenia na powierzchni tylnej stopy niż na powierzchni przedniej zarówno w stopie lewej (odpowiednio 61,9% i 37,9%) jak i prawej (odpowiednio 59,9% i 40,1%).
Wnioski. Wyniki badań autorów dostarczają użytecznych wartości referencyjnych dla cech morfologicznych i sprawności kończyn dolnych u elitarnych zawodników BJJ. Ponadto, po raz pierwszy w tej populacji oceniono parametry baropodometryczne, wykazując, że czynniki takie jak ciśnienie plantacyjne i rozkład obciążenia plantacyjnego są większe w stopie niedominującej i na tylnej powierzchni obu stóp.