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"Ido Movement for Culture Journal of Martial Arts Anthropology",
Vol. 24, no. 3 (2024), pp. 12–22
DOI: 10.14589/ido.24.3.2

PHYSICAL ANTHROPOLOGY

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Body composition, power muscle, and baropodometric assessment in elite Muay Thai athletes

Submission: 18.07.2022; acceptance: 21.11.2022

Key words: power muscle, anthropometric evaluation, somatotype, plantar pressure

Abstract
Background. *Muay Thai* is a dynamic fighting style which has existed for over 2000 years and consists of using a multitude of fists, kicks, and knee and elbow strikes to knock out the opponent. Studies indicate that the general physiologic profile of Muay Thai athletes is high anaerobic power and muscular strength, with low body fat percentage and a mesomorphic somatotype.
Problem and Aim. Evaluate morphological, physical and baropodometric characteristics of elite male Muay Thai athletes.
Methods. Fifteen elite Muay Thai athletes performed the following tests: Anthropometric measurement, lower limb muscle power and baropodometric assessment in static conditions.
Results. Athletes presented body fat percentage (10.8 ± 3.8%) and balanced mesomorphic somatotype (2.3- 5.5-2.1). In lower limb strength performance, we observed measures of 44.7 ± 4.4 cm, 1640 ± 284 N, and 4.1 ± 3.6 % in vertical jump height, maximum force and bilateral asymmetry index percentage respectively. Additionally, baropodometric analysis revealed higher maximum force values in the heel and metatarsal zones ($p<0.01$ and $p< 0.05$, respectively). On the other hand, peak pressure and load distribution

For citation – in IPA style:
Quintero A.M., Fuentes-Garcia J.P., Poblete-Valderrama F., de Andrade G.A.P., De la Rosa A. (2024), *Body composition, power muscle, and baropodometric assessment in elite Muay Thai athletes*, "Ido Movement for Culture Journal of Martial Arts Anthropology", vol. 24, no. 3, pp. 12–22; doi: 10.14589/ido.24.3.2.
In other standard – e.g.:
Quintero, A.M., Fuentes-Garcia, J.P., Poblete-Valderrama, F., de Andrade, G.A.P., De la Rosa A. Body composition, power muscle, and baropodometric assessment in elite Muay Thai athletes. *Ido Mov Cult J Martial Arts Anthrop*, 2024, 24 (3): 12–22 DOI: 10.14589/ido.24.3.2

values were higher in the dominant foot (p<0.05). Moreover, we observed a higher load distribution percentage on the rearfoot surface than the forefoot surface in both the left (58.7% and 41.3%, respectively) and right foot (64.3% and 35.7% respectively). Conclusions. These results provided a profile of elite Muay Thai athletes that could be used as training and tactical targets for developing athletes.

Introduction

Muay Thai is known in the world of martial arts generally as Thai Boxing or the art of "the eight limbs", a name given because it uses both the upper and lower extremities of the human body to hit its opponents [Moore 2008; Monterrosa, Moro 2020]. The popularity of this martial art has grown significantly over the last decade, even gaining provisional recognition as an Olympic sport [IFMA 2016]. Muay Thai requires complex skills, technical, and tactical abilities since fighters use fists, elbows, kicking, and knee techniques to attack each other during 3 rounds of 5 minutes. Likewise, each fighter uses different parts of the body as a shield to block the techniques used by the opponent [Delp 2004; Turners 2009; Cimadoro, Mahaffey, Babault 2018].

Muay Thai, similar to Kickboxing, is a high-intensity, dynamic and intermittent striking combat sport that requires complex skills and tactical excellence for success, where athletes are classified by gender, body mass, and age categories [Slimani *et al.* 2017]. On the other hand, the combination of upper and lower limb movements, including those in which the athletes are in no contact with the ground during the combat, requires advanced balance and coordination skills [Haksever *et al.* 2021], but there is research evaluating the relationship between Muay Thai and balance. Thus, many of the most important variables involved in this martial art are related to body composition, muscle power and the plantar pressures to achieve optimal results [Jungman, Wilson 2016; Monterrosa *et al.* 2019].

Considering the aforementioned variables can facilitate training programming as well as the prevention of sports injuries resulting from different striking techniques [Teodoru, Razvan 2014; Jungman, Wilson 2016]. However, there is a limited number of studies in the literature investigating these variables in elite Muay Thai athletes.

According to the above information and since Muay Thai 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 body composition characteristics of elite Muay Thai athletes; (ii) to evaluate lower limbs performance and (iii) to present reference values for different baropodometric parameters in this population.

Materials and methods

Design and Participants

This is a cross-sectional analytical study that defined the anthropometric profile and reference values of lower limb strength and plantar pressures of Muay Thai fighters.

Fifteen male MMA athletes experienced in national-level competition took part in the study (aged: 29.4 ± 6.3 years; weight 77.8 ± 12.5 kg; height 178 ± 8.6 cm and 8.5 ± 4.0 years of training experience). The athletes were recruited from various sports academies in the state of Santa Catarina (Brazil), with the support of several coaches. These athletes were engaged in regular training 5 days per week and were in the preparatory period.

Inclusion criteria were as follows: (a) fighters between the ages of 18 and 40-year-old; (b) be a competitor athlete with national or international experience; (c) be exempt from any physical injury; (iv) be currently training with a frequency of at least 5 days of training a week; (v) apparently healthy; (vi) to complete all anthropometric and physical assessments; (vii) be a *right- leg dominant* athlete. After being informed of the procedures to which they would be submitted, all subjects signed an Informed Consent Form. Participants presenting altered foot arch (i.e. excessive fallen arch or high arch) were not included in this study to avoid bias in plantar pressure distribution [Chuckpaiwong, Nunley, Queen 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 from training for 24 h before data collection. Subsequently, data were collected on two different days in the biomechanics laboratory of the Federal University of Santa Catarina, during the preparatory stage (pre-season) in the morning hours (8:00–10:00 a.m.) at 25 °C in fasting conditions.

During the first visit to the laboratory, the anthropometry measures and jumping tests were performed. The other visit to the laboratory took place the next day in order to perform the baropodometric assessment.

Evaluations were conducted in the following order: anthropometry, countermovement jump and finally the baropodometric assessment.

Anthropometry

All variables were taken by a level-3 anthropometrist, in accordance with the international standards for anthropometric assessment published by the International Society for the Advancement of Kinanthropometry – ISAK.

Athletes underwent measurements of body mass (kg) and height (cm) using a medical digital scale to the nearest 100 g (SWAN, Pekin, China) and a fixed adult stadiometer (CESCORF, Porto Alegre, Brazil) with precision of 0.5 cm, respectively.

The skinfold thickness of the biceps, triceps, subscapular, suprailic, supraspinal, abdomen, anterior thigh, and medial calf regions were measured with a skinfold caliper (CESCORF, Porto Alegre, Brazil). The measurement of the girths (arm [relaxed], arm [flexed], forearm, thorax, waist [minimum], gluteal [hips], thigh, and calf [maximum]) was carried out using a constant-tension steel tape (CESCORF, Porto Alegre, Brazil). Breadths were measured for humerus and femur segments using a Rosscraft Campbell 20 anthropometer for large bones with a measurement range of 54 cm and an accuracy of 0.1 cm. For data analysis, averages of two measurements of each anthropometric variable were calculated and processed.

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 × (TG/π - TSF)^2 - (0.3×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 × (UARG^2))– BW) / 1000	[Rodriguez *et al.* 2010]
MMLL	(((H - ΣTCP) × (TB)^2) + (GT + CG)) /1000	[Rodriguez *et al.* 2010]
TBSM	Ht × (0.00744 × CAG^2 + 0.00088 × CTG^2) + (0.00441 × CCG^2) + 2.4 (sex – 0.048 × 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; BW, Body Weight; 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.

Morphology and body composition

To perform the morphological characterization, we analyzed the raw data obtained for each anthropometric variable (skinfolds, breadths, and girths) and calculated 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, Carter 1967]. From these measurements, we estimated different anthropometric indices according to the formulas presented in **Table 1**.

Vertical jump and bilateral asymmetry index assessment (BAI)

Vertical jump performance was assessed by Countermovement jump (CMJ), using an electronic force platform (Quattro Jump, Kistler, Switzerland) with a sampling frequency of 500 Hz, as previously described Monterrosa *et al.* [2023]. Briefly, after five minutes of light warm-up, athletes performed self-administered submaximal CMJ trials to practice the technique (4 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. Each athlete 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, athletes placed one leg on the force platform and the contralateral leg on a wooden base at the same level **(Figure 1).** The force platform and wooden base were positioned 2 cm apart to avoid contact. BAI was quantified using the equation proposed by Impellizzeri *et al.* [2007].

BAI

Baropodometry assessment

During baropodometric test, athletes were asked to stay in an orthostatic position for 60 seconds, gazing forward, barefoot with feet placed side-by-side and arms held along the trunk on the platform electronic platform MobileMat (Matscan, Tekscan, Inc., Boston, USA). The sampling frequency was set at 100 Hz. The following parameters were considered on both feet: the percentage of distribution of load between rearfoot and forefoot, peak power, maximum force right, and peak pressure variable. Data were processed using the FootMat Research 7.10. software. Figure. 2 shows the pressure distribution regions for Muay Thai athletes.

*Statistical analysis_*

All statistical analyses were carried out using Jamovi Software® version 1.6 (https://www.jamovi.org), an opensource software that is freely available. We calculated a Pearson's correlation when data followed a normal distribution. The alpha level was set to 0.05. Normality of distribution was checked with the Shapiro-Wilk test.

Figure 1. Image of an athlete standing on the force (left leg) and wooden (right leg) platforms during a CMJ test.

Figure 2. Foot outline with seven 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. Numbers 5, 6 and 7 correspond to the rearfoot.

Likewise, when we compared baropodometric parameters between right and left feet, we used a two-tailed paired Student's test. Data were expressed as mean ± standard deviation, range and confidence intervals (95%).

Table 2. Morphological characteristics of Muay Thai practitioners.

	Mean ± SD	Range	95% CI	
Breadth (cm)				
Humerus	7.1±0.3	6.7 to 7.8	7.0	7.3
Rigth femur	9.7±0.4	9.1 to 10.7	9.4	9.9
Left femur	9.7±0.4	9.2 to 10.6	9.4	10
Girth (cm)				
Upper arm relaxed	32.9±3.0	27.2 to 38.3	31.2	34.6
Upper arm tensed	35.7±3.0	30.5 to 41.1	34	37.4
Rigth thigh	56.2±4.5	48.4 to 65.2	53.6	58.7
Left thigh	56±4.6	47.2 to 64	53.4	58.5
Right calf	37±2.5	33 to 40.9	35.6	38.4
Left calf	36.8±2.4	33 to 40.9	35.5	38.2
Waist	81.8±6.5	74.1 to 94	81.4	87.9
Hip	96.8±6.0	87.7 to 110	93.4	100.2
Skinfolds (mm)				
Biceps	2.8±0.8	2.0 to 5.0	2.2	3.4
Triceps	6.7±2.0	5.0 to 11.0	5.4	8.0
Subscapular	9.1±2.1	6.5 to 14.0	7.8	10.4
Suprailiac	12.3±3.1	7.8 to 17.3	10.3	14.3
Supraspinal	6.6±2.9	4.0 to 12.0	5.3	7.9
Abdominal	13.2±5.1	7.0 to 23.0	10.1	16.4
Right thigh	11.0±3.6	5.0 to 18.0	8.7	13.3
Left thigh	10.7±3.8	5.0 to 19.0	8.3	13.1
Right calf	6.9±3.1	3.0 to 14.0	4.9	8.9
Left calf	7.2±3.5	3.0 to 14.0	4.9	9.4

Results

In combat sports, such as Muay Thai, knowledge of body composition is essential to outline the athlete's fitness profile, as well as being useful for the definition of his or her weight class. Likewise, body composition plays a major role in martial arts in that it determines physical performance (Monterrosa, Moro, 2020). For instance, higher levels of body fat are negatively correlated with performances of muscular power of lower limbs and strength endurance [Marinho, Vecchio, Franchini 2011]. Athletes in the present study had a mean BF % of 10.8 and a balanced mesomorph somatotype (2.3-5.5-2.1), ranging from 0.9–5.1 for endomorphy, 3.4–7.5 for mesomorphy and 0.6–4.0 for ectomorphy. **Tables 2** and **3** provide descriptive results of anthropometric characteristics and body composition for elite Muay Thai athletes. Likewise, to ease the interpretation of the somatotype results, a graphical description of individuals' values is shown in **Figure 3.**

Table 3. Body composition and somatotype of elite Muay Thai athletes.

	Mean ± SD	Range	95% CI	
Somatotype				
Endomorphy	2.3 ± 1.0	0.9 to 5.1	1.7	2.9
Mesomorphy	5.5 ± 1.1	3.4 to 7.5	4.9	6.1
Ectomorphy	2.1 ± 1.0	0.6 to 4.0	1.5	2.7
Anthropometric indicators				
FM (kg)	8.8 ± 4.7	4.5 to 21.2	5.8	11.8
FFM (kg)	69.0 ± 7.5	58.4 to 85.3	64.5	73.8
FMI (kg. m–2)	2.8 ± 1.5	1.0 to 6.8	1.9	3.6
FFMI (kg. m–2)	21.6 ± 1.7	18.5 to 24.5	20.5	22.7
BMI (Kg. m^{-1})	24.3 ± 2.1	20.6 to 27.4	22.9	26.0
Σ6 skinfolds (mm)	58.4 ± 21.0	38.5 to 107.5	45.0	72.0
Σ8 skinfolds (mm)	75.2 ± 27.0	52 to 140	58.1	92.4
Body fat %	10.8 ± 3.8	7.2 to 29.9	8.4	13.3
Muscle mass in upper limbs (kg)	7.9 ± 1.3	6.2 to 10.7	7.1	8.7
Muscle mass in lower limbs (kg)	15.0 ± 1.7	13.2 to 19.2	13.9	16.1
WHTR (m)	0.4 ± 0.0	0.4 to 0.5	0.4	0.5
WHR	0.8 ± 0.0	0.8 to 0.9	0.8	0.9
RPI (cm. kg^{-1})	41.9 ± 1.4	39.6 to 44.5	41.1	42.9
BADI	22.6 ± 2.1	19.8 to 26.6	21.3	24.0
CSA Right thigh (cm^2)	192.0 ± 20.1	160.5 to 223.8	179.2	204.8
CSA Left thigh (cm^2)	195.4 ± 26.1	157.7 to 240.5	178.9	212.2

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 iliocrestal)*; WHTR, waist to height ratio; WHR, waist to hip ratio; RPI, reciprocal ponderal index; BADI, body adiposity index; CSA, cross-sectional area.

It has been previously described that the energetic demands in Muay Thai matches depend on both oxidative and glycolytic systems [Crisafulli *et al.* 2009]. In addition, decisive movements during combat such as \ kicking, punching, elbowing and knee-striking, as well as holds, and grabbing techniques have an explosive nature. In the present study, lower limb muscle strength was measured by using CMJ test.

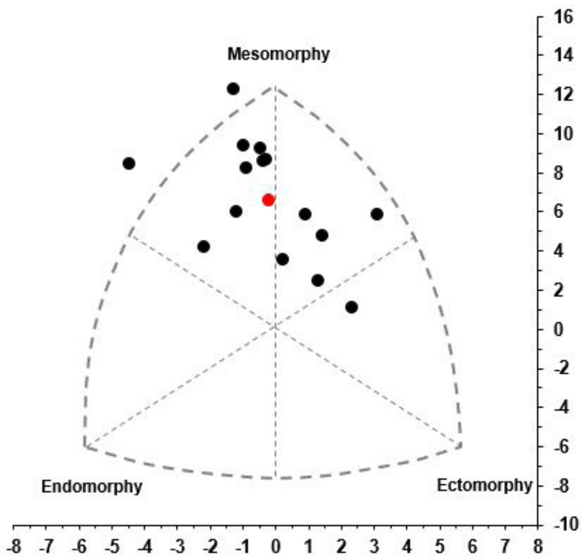

Figure 3. Somatotype distribution (somatochart) of elite Muay Thai athletes.

Table 4 provides results in vertical jump performance. Overall, regarding vertical jump performance, analyses showed that athletes jumped ~45cm with a relative peak force, relative peak power and relative peak of velocity of ~21 N.kg^{-1} and ~48 W.kg^{-1} and 2.6 m. $s^{1,}$ respectively.

Table 4. CMJ performance parameters in Muay Thai athletes.

Vertical jump performance	Mean ± SD	Range	95% CI	
Jump height (cm)	44.7 ± 4.4	38.2 to 57.8	42.2	47.1
Maximum $force_{both}$ (N.)	1640 ± 284	1199 to 2128	1482	1797
Maximum $force_{both}$ (N.kg^{-1})	21.2 ± 2.7	18.9 to 29.3	19.6	22.6
Maximum force right leg (N.)	818 ± 123	610 to 999	749	886
Maximum force left leg (N.)	827 ± 134	582 to 1026	752	900
Maximum force right leg (N.kg^{1})	10.6 ± 1.1	9.2 to 13.2	9.9	11.2
Maximum force left leg (N.kg^{1})	10.7 ± 1.1	9.2 to 13.3	10.0	11.2
Peak $power_{both}$ (W.kg^{1})	48 ± 5.6	39.7 to 60	44.8	51.1
Peak $velocity_{both}$ (m. s^{1})	2.6 ± 0.1	2.4 to 3.2	2.5	2.7
BAI (bilateral asymmetry index, %)	4.1 ± 3.6	0.3 to 11.6	2.1	6.1

To determine if anthropometric variables correlated with physical performance in lower limbs, we plotted the cross-sectional area in both right and left thigh against the maximum force in the right and left legs respectively, during vertical jump. As shown in **Figures 4A, B** there was a significant, moderate and strong correlation in both cases (r=0.56, p<0.05 and r=0.87, p<0.001 respectively). Interestingly, no further significant correlations were found. All the athletes were included in the correlation study.

We then analyzed the baropodometric characteristics of the participants. The analysis showed greater levels of maximum force in both the left rearfoot and

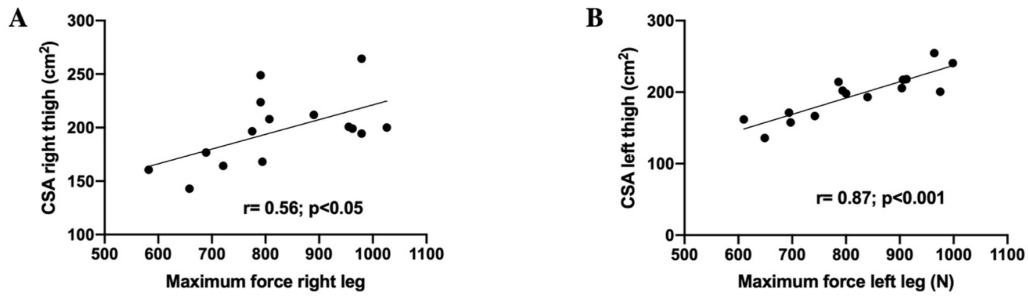

Figure 4. Bivariate correlations between anthropometric and physical performance parameters
Pearson's correlation test between CSA thigh and maximum force in right leg (A) and left leg (B). For both, values inside the graph indicate the p value of the correlation.

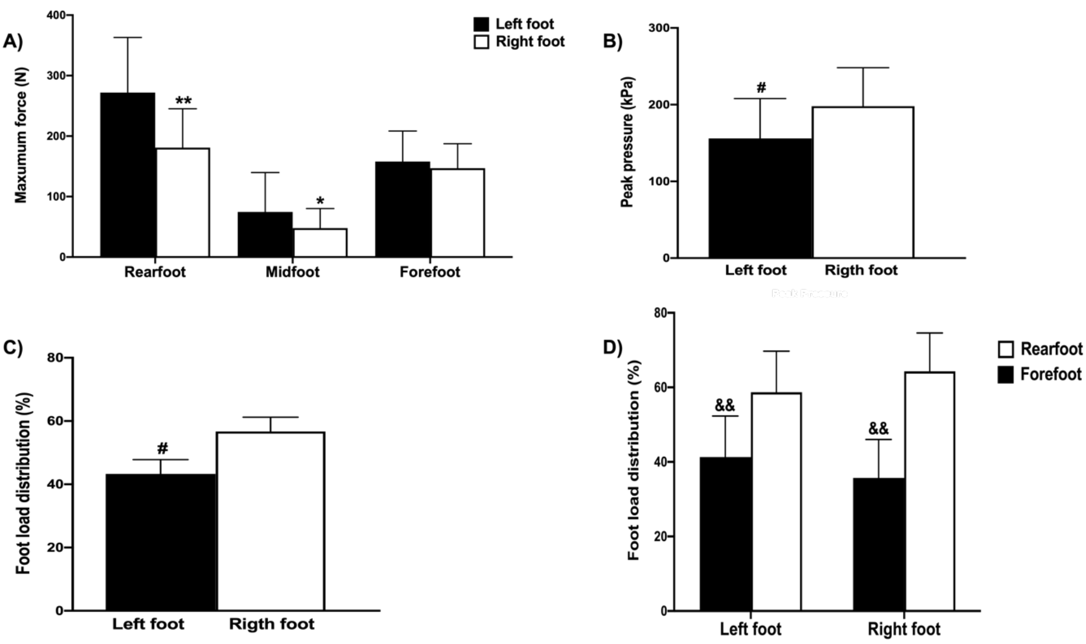

Figure 5. Baropodometric analysis in elite Muay Thai athletes.
(A) Maximum force in rearfoot, midfoot and forefoot (B) Peak pressure on both feet (C) Percentage of load distribution on feet and (D) Percentage of load distribution between forefoot and rearfoot on both feet. Bars represent Mean ± SD. Statistical significance was assessed using a 2-tailed paired Student's t test. */**/ denotes p<0.05/ 0.01/vs respective zone in the left foot, # p<0.05 vs right foot, && p<0.01 vs rearfoot.

left midfoot than those in the right foot (272.0 ± 91.0 N and 74.6 ± 65.2 N vs 181.0 ± 64.2 N and 47.9 ± 32.3 N, respectively: **Figure A**). Moreover, peak pressure was greater in the right foot than the left foot (198.0 ± 50.1 vs 156 ± 51.9 kPa, respectively; **Figure B**). In addition, significant differences were found in foot load distribution percentage between the left and right feet (56.1 ± 5.0 vs 43.9 ± 5.0, respectively) (Figure **C**). Finally, as shown in **Figure D**, greater levels of load distribution percentage were found in the rearfoot of both feet than the forefoot. T-test plots are shown in **Figure 5**.

Discussion

In this cross-sectional study, we provide an overview of morphological characteristics in Muay Thai athletes and describe different performance variables related to vertical jump performance and baropodometric measures. Among the main findings, we report a vertical jump height higher than those reported by other research in combat sports. Moreover, we found significant differences (p< 0.01) in baropodometric measures between feet, and when we compared the rearfoot and forefoot surfaces in both left and right foot.

Somatotype and body composition

In martial arts, the knowledge of body composition is essential to define the athlete's fitness profile, besides being useful for the definition of his weight category [Marinho *et al.* 2016]. In that regard, the athlete's body composition is a parameter to be evaluated, which is related to physical performance [Monterrosa *et al.* 2023]. Thus, several types of research have negatively associated body fat and body composition with physical and technical performance in combat sports from *judo* [Franchini *et al* 2005], *Jiu-Jitsu* [Kons *et al.* 2017], *Taekwondo* [Antunez *et al.* 2012], *Wushu* [Tan *et al.* 2022] and Wrestling athletes [Yoon 2002].

In the same way, some evidence has shown that in Martial Arts %BF of well-trained athletes is predominantly low, with values ranging from 8.5% to 13.5% [Lovell, Bousson, McLellan 2013; De Oliveira *et al.* 2015; Marinho *et al.* 2016; Tan *et al.* 2022] [Siqueido 2010; Lovell *et al. 2013;* Marinho *et al.* 2016; de Oliveira *et al.* 2015; Tan *et al.* 2021].

These values are consistent with those we noted in our study (mean, 10.8%; 95% CI, 8.4%-13.3) and those reported by Mortatti *et al* [2013] and Baron [2016] in 9 and 12 well-trained Brazilian Muay Thai athletes (mean of 12.0 % and 13.3%, respectively). Similar data were recently observed by Cannataro *et al* [2020] in High-level Muay Thai athletes (mean, 11.46%; 95% CI, 10.7%-12.2). The lowest body fat percentage in the Muay Thai athletes in our study might be due to the practice of severe weight control methods by most of the fighters or the period of training which athletes are in. Also of note, there were several equations used to calculate body fat percentage in the studies mentioned above and any direct comparison between findings could be inappropriate [Monterrosa *et al.* 2022].

Nonetheless, the balanced mesomorph somatotype in the present study, typical of elite athletes, was consistent with previous reports in combat sports athletes, including Muay Thai [Andreato *et al.* 2017; Krick, Raschka. 2018; Monterrosa *et al.* 2023], indicating a strong development of muscle mass and bone structure which are required to guarantee defensive actions. Likewise, somatotype also seems important in national-level fighters to offensive actions, which tend to prefer knee strikes [Myers *et al.* 2013].

Lower limbs performance

Vertical jump performance is regarded as a good indicator of maximal neuromuscular power and explosiveness in the lower limbs [Kons *et al.* 2017]. Among vertical jump test, CMJ is a reliable and largely used *tool* to measure *lower-limb* power capacity in sports, including combat sports [Huang *et al.* 2018; James *et al.* 2020; Tan *et al.* 2022; Monterrosa *et al.,* 2023]. Because kicks and kneeing techniques in Muay Thai require high muscular strength and power in the lower limbs, the force produced during the CMJ test is a relevant measure.

Analyses of the CMJ performance variables in our study were higher than those previously reported in Brazilian Jiu-Jitsu athletes by our research group [Monterrosa *et al.* 2023]. In addition, several studies in combat sports athletes, including Muay Thai, have reported that height reached between 27 to 48 cm in the CMJ test [Hammami *et al.* 2014; Ramirez-Velez *et al.* 2014; Diaz-Lara *et al.* 2015; Andreato *et al.* 2016; Cimadoro, Mahaffey, Babault 2018; Spanias *et al.* 2019; Follmer *et al.* 2021; Tan *et al.* 2022].

Muscular force and power are important in crucial moments of combat sports. For this reason, it is important to permanently monitor these variables in order to estimate athletes' capacity to compare it with other training periods and reference groups [Franchini *et al.* 2011; Bridge *et al.* 2014]. Previous studies have shown the interplay between peak velocity and vertical jump performance. Moreover, Loturco *et al.* [2017] reported that increased jump height and power appear to have a meaningful transfer to certain martial art movements for the elite boxing athletes.

Muay Thai athletes require fast energy mainly from the phosphagen system during the combat to perform high-intensity decisive attacking techniques, including a variety of punches (straight, hook and uppercut), kicks (Roundhouse kick, Push kick and teep kick), kneeing and elbowing. However, Muay Thai training puts more emphasis on the strength of the legs, since kicking and kneeing are predominant offensive strategies in this martial art [Saengsirisuwan 1998].

In the present study a mean of ~45cm in vertical jump in elite Muay Thai athletes with relative maximum force, relative peak power and peak velocity of ~21 N. Kg^{-1}, 48 $W.kg^{-1}$ and 2,6 m. s^1 respectively, were found **(Table 4)**. These findings in the CMJ test were higher than those reported by Cimadoro and Bayer groups in Muay Thai athletes (27,3 cm and 31,9 cm, respectively). Along with the above, we found significant correlations between jump height with peak velocity and peak power ($r = 0.9$, $p < 0.001$; $r = 9.7$, $p < 0.01$, respectively) (data not shown). In this sense, our results demonstrated that athletes in this study presented important levels of strength and power in the lower extremities, higher than those reported in other combat sports, 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 the right and left thigh ($r = 0.56$, $p<0.01$ and $r = 0,87$, $p<0.001$ 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 Muay Thai athletes.

Baropodometric characteristics

The foot serves as a base of support and propulsion for movement during activities of daily living, as well as sports [Rosario 2014]. The plantar arches absorb ground reaction forces during sports [Dahle *et al.* 1991]. Along with this, physical training alters locomotion patterns and baropodometric parameters such as load distribution, pressure and force of the plantar structure, which might be at higher risk of a stress injury in the foot. Numerous studies have shown variations of plantar support in athletes, including these in combat sports [Ripani *et al.* 2006; Feka *et al.* 2019; Barczyk-Pawelec, Hawrylak, Chromik 2021; Hawrylak, Brzezna Chromik. 2021; Mocanu *et al.* 2021]. Regarding Muay Thai, the nature of this sport makes that balance important to maintain a good defense and resist going down.

Here we wondered whether high-performance Muay Thai practice could alter foot support patterns between feet. Statistical analyses revealed asymmetric rearfoot and midfoot maximum forces, with higher values on the left foot **(Figure 4A)**. In this study, all athletes were right-leg dominant. To the best of our knowledge, no research reported baropodometric parameters in different foot regions in Muay Thai athletes. However, results in the present study are similar to those reported by our research group in well-trained Brazilian Jiu-Jitsu athletes [Monterrosa *et al.* 2023]. These higher values in maximum force in the non-dominant foot (left foot) could be due to a greater predisposition of the left foot to work in defensive situations, serving as support during offensive movements performed by the opposing leg, which require balance.

On the other hand, values of both peak pressure and foot load distribution were higher on the right foot (**Figures 4B, C**).

Previous reports showed that professional Muay Thai fighters delivered almost three times more attacking techniques than defensive techniques during combat, with kicking techniques being the most frequently employed [Myers *et al.* 2013]. In this regard, higher pressure and load distribution values in the *dominant foot, in the present study,* may result from a greater predisposition of the right foot to work in offensive situations such as kicking and knee-striking. Recent reports have also indicated higher values of plantar pressure on the dominant foot in adolescent karate practitioners [Mocanu *et al.* 2021]. Furthermore, it has been described that specific strikes to Karate-do were strongly influenced by the maximal pressure on each foot [Daniel, Razvan-Liviu 2014].

Thus, results in the present study could indicate an adaptation of our athletes derived from applying higher amounts of pressure the dominant foot over the mat during combat, in order to execute techniques such as double kicks or consecutive knees to an opponent. These actions require that after each strike, the leg will be quickly driven back down into the ground and then quickly driven back up towards the opponent. However, there is a lack of studies evaluating these baropodometric parameters in Muay Thai athletes, which prevents us from corroborating the hypothesis proposed above.

In addition, differences were observed between the rearfoot and forefoot in foot load distribution in both feet **(Figure 4D)**. Fighters showed a higher load distribution percentage in the rearfoot than the forefoot surface in both the left (58.7% and 41.3) and right foot (64.3% and 35.7% respectively). Our findings do not agree with those previously reported in soccer players, rowers, dancers, swimmers and judokas [Feka *et al.* 2019]. However, values reported in the study by Feka came from the sum of different sports and not from individual analyses, which makes it difficult to compare with the results in the present study. Recent reports of our research group in BJJ athletes were similar to those found in the present study, with the rearfoot exhibiting a higher load distribution percentage than those in the forefoot [Monterrosa *et al.* 2023]. In this regard, we believe that this characteristic in plantar support is due to the specificity of this martial art. Thus, a greater distribution of the load on the rearfoot in both feet may generate more stability in different situations during the fight in different techniques (movements across the mat and movements before defensive and offensive actions) [Monterrosa, Moro 2020]. However, more studies are needed to corroborate this hypothesis.

Conclusions

Body composition and somatotype in elite Muay Thai athletes were similar to those reported in studies with martial arts athletes. Thus, our study contributes to increased knowledge about this aspect. These results are important, as the regulation of body mass is a major concern in this sports discipline.

On the other hand, the findings of the present study related to physical performance in lower limbs provide a profile of elite Muay Thai athletes, as there are not many reports in the literature on this population. Thus, this study expands the understanding that high levels of strength and power along with low percentages of asymmetry are characteristic of top-level martial arts athletes and can help Muay Thai instructors in the selection of athletes and in the preparation of appropriate training programs.

Finally, our results provide novel information on the baropodometric parameters of elite Muay Thai athletes and confirm the predisposition of dominant and non-dominant foot, respectively, to work in offensive and defensive situations, with the rearfoot being the area that receives the most load. Our results can be used to know the predisposition of plantar supports in physically healthy fighters. in this way, a different distribution of both loads and plantar pressures from those reported in our study could alert trainers about the risk of lower limb injuries. However, these results should be viewed with caution, due to the absence of a control group in our research.

Limitations of the study

The study had several limitations that should be discussed and considered for future research. First, the sample of volunteers was limited, due to the few number of investigated subjects generated by the lower specificity and popularity of this sport. However, our sample is of valuable as avowed elite athletes. Secondly, the absence of a control group (not involved in any sport) did not allow for the identification of the differences between Muay Thai athletes and those of the same age who do not have these concerns. We would like to mention that there are no cross-sectional or longitudinal studies that performed baropodometric analysis on Muay Thai athletes. 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 Muay Thai athletes in different competitive levels to enhance our knowledge regarding both baropodometric static and dynamic profiles of Muay Thai fighters and their relationship with physical performance.

Acknowledgments

We would like to warmly thank all the athletes who participated in the study.

Data Availability Statement

All data are available from the corresponding author upon reasonable request.

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Skład ciała, siła mięśni i ocena baropodometryczna u elitarnych zawodników Muay Thai

Słowa kluczowe: mięśnie siłowe, ocena antropometryczna, somatotyp, ciśnienie podeszwowe

Streszczenie

Tło. Muay Thai to dynamiczny styl walki, który istnieje od ponad 2000 lat i polega na użyciu pięści, kopnięć, uderzeń kolanami i łokciami w celu znokautowania przeciwnika. Badania wskazują, że ogólny profil fizjologiczny sportowców Muay Thai to wysoka moc beztlenowa i siła mięśni, z niskim procentem tkanki tłuszczowej i mezomorficznym somatotypem.

Problem i cel. Ocena cech morfologicznych, fizycznych i baropodometrycznych elitarnych zawodników Muay Thai.

Metody. U piętnastu elitarnych zawodników Muay Thai wykonano następujące testy: pomiar antropometryczny, siła mięśni kończyn dolnych i ocena baropodometryczna w warunkach statycznych.

Wyniki. Sportowcy charakteryzowali się procentową zawartością tkanki tłuszczowej w organizmie (10,8 ± 3,8%) i zrównoważonym somatotypem mezomorficznym (2,3- 5,5-2,1). W zakresie siły kończyn dolnych zaobserwowano odpowiednio 44,7 ± 4,4 cm, 1640 ± 284 N i 4,1 ± 3,6% wysokości skoku pionowego, maksymalnej siły i dwustronnego wskaźnika asymetrii. Dodatkowo, analiza baropodometryczna wykazała wyższe wartości siły maksymalnej w strefie pięty i śródstopia (odpowiednio p<0,01 i p<0,05). Z drugiej strony, szczytowe wartości ciśnienia i rozkładu obciążenia były wyższe w stopie dominującej (p<0,05). Ponadto zaobserwowano wyższe obciążenie oraz większy procentowy rozkład obciążenia na powierzchni tylnej części stopy niż na powierzchni przedniej części stopy zarówno w lewej (odpowiednio 58,7% i 41,3%), jak i prawej stopie (odpowiednio 64,3% i 35,7%).

Wnioski. Wyniki te dostarczyły profilu elitarnych sportowców Muay Thai, który można wykorzystać jako cele treningowe i taktyczne dla rozwijających się sportowców.