Biomechanical characteristics of amateur boxers

Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Manuscript Preparation
E Funds Collection

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Received: 05 May 2016; **Accepted:** 20 August 2018; **Published online:** 29 January 2019

AoBID: 11135

ABSTRACT

Background and Study Aim: The success in a boxing match is determined by many mutually correlated factors, such as motor abilities, technique, tactics, mental aptitudes of a boxer and method of judging. The aim of the study was to verify whether: 1) maximum force developed for an individual straight and hook punch performed with the lead hand is lower than the punching force recorded for the rear hand; 2) isometric peak joint torques for the upper lead limb are lower than joint torques for the rear hand; 3) there is a relationship between the maximal punching force and maximal torques, power output and jumping abilities of boxers.

Material and Methods: Six boxers participated in this study. The following measurements were taken: height of the jump and power output in countermovement jump (CMJ) and spike jump (SPJ), muscle strength of 10 muscle groups, force-velocity relationship (F-v), and force of punches for the rear and lead hand (hook and straight punches).

Results: Mean maximal straight punching forces with the rear, and lead hand were 2478.8 ±558.4 N and 1472.8 ±472.6 N, respectively. Mean maximal straight and hook punching forces were 2599.7 ±576.3 N and 2192.2 ±888.5 N, respectively. The values of the height of CMJ and SPJ jumps were 0.430 ±0.050 m and 0.511 ±0.068 m, respectively. Peak power developed during individual straight punches with the rear limb was significantly higher than the maximal force of the punch performed with the lead limb. Peak joint torques for the lead limbs did not differ statistically from the joint torques for the rear limbs. A high correlation is observed between maximum punching force and strength, the height of CMJ and SPJ jumps and power output developed during the determination of the F-v relationship.

Conclusions: Lack of differences in the values of forces between the rear and lead limbs and finding correlations between the punching force and the muscle torques are likely to show that the punching force may depend on other factors, e.g. technique.

Keywords: countermovement jump • F-v relationship • joint torque • power • punching force • spike jump

Conflict of interest: Author has declared that no competing interest exists

Ethical approval: The study was approved by the Local Ethical Committee at the Institute of Sport – National Research Institute (Warsaw, Poland) and the Senate Research Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw (Warsaw, Poland)

Provenance & peer review: Not commissioned; externally peer reviewed

Source of support: The study was supported by the Ministry of Science and Higher Education (Grants: Józef Piłsudski University of Physical Education in Warsaw, No. DS. 134 and Institute of Sport – National Research Institute, No. K.4.1.)

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Hook *noun* **1.** (*in boxing*) a short blow to an opponent delivered with a swing and a bent arm (…) ▪ *verb* **1.** (*in boxing*) to deliver a sharp curving blow to an opponent, using a curved or bent arm (…) [29].

Punch *verb* to strike someone or something with the fist, e.g. in boxing or martial arts [29].

Tactics – *plural noun* the art of finding and implementing means to achieve immediate or short-term aims [29].

Technique– *noun* a way of performing an action [29].

Power *noun* **1.** physical force or strength **2.** the ability, strength, and capacity to do something [29].

INTRODUCTION

The success in a boxing match is determined by many mutually correlated factors, such as motor abilities, technique, tactics, mental aptitudes of a boxer and method of judging [1]. There are no extensive studies on biomechanical and physiological characteristics of boxers in the literature [2-4]. Guidetti et al. [3] found a significant relationship between the sport skill level and perceived physical activity (PPA) values (r = 0.91), as well as upper limb force (r = 0.87), measured using a manual dynamometer. In a study by Smith et al. [5], the researchers demonstrated that the straight punching force for the rear hand is greater than for the lead hand. The same authors showed that the punching force depends on the sport skill level of boxers (national team, adult boxers, junior boxers). Furthermore, Karpiłowski et al. [2] found a relationship between the punching force and peak joint torques for selected muscle groups. A study by Loturco et al. [6] demonstrated a relationship between the jump height and punching force.

The aim of the study was to verify whether: 1) maximum force developed for an individual straight punch and hook punch performed with the lead hand is lower than the maximum punching force recorded for the rear hand; 2) peak joint torques for the upper lead limb measured under isometric conditions are lower than the maximal torques for the muscle torques for the rear hand; 3) there is a relationship between the maximal punching force and maximal torques, power output and jumping abilities of boxers.

MATERIAL AND METHODS

Participants

Six boxers (age: 16.8±1.0 years, body height: 185.7±6.0 cm, body mass: 75.8±7.0 kg, training experience: 2.1±1.2 years) participated in this study. Ethical approval for this study was provided by the Local Ethical Committee at the Institute of Sport – National Research Institute, Warsaw, Poland and the Senate Research Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw, Poland. Written informed consent was obtained from participants or their parents if a participant was under 18 years of age. The study was conducted in accordance with the Declaration of Helsinki.

Study design

Power output and jump height

The power output of lower extremities and the height of rise of the body's centre of mass (COM) during vertical jumps were measured using the Kistler force plate Type 9281A (Kistler Instrumente AG, Winterthur, Switzerland) with the Kistler amplifier Type 9865 B 1 Y28 (Kistler Instrumente AG, Winterthur, Switzerland). The amplifier was connected to a computer via an A/D converter. The MVJ software package ("JBA" Zb. Staniak, Poland) was used for measurements. In the physical model used in the study, the participant's body mass bouncing on the force plate was reduced to a particle affected by the vertical components of external forces: the body's gravity force and the vertical component of the platform's reaction force. Peak power (P_{max} [W]), relative peak power (P_{max}·mass^{-1} [W·kg^{-1}]) and maximal height (h [m]) of the rise of the body's COM were calculated from the recorded ground reaction force of the platform.

Each participant performed six vertical jumps on the force plate: three counter-movement jumps (CMJs) and three spike jumps (SPJs). The characteristics of each jumping test were the following: **CMJ** – a vertical jump from a standing erect (vertical) position, preceded by a counter movement of upper limbs and with lowering of the body COM before the take-off; **SPJ** – a vertical jump which is performed with a 3-4 step run-up before the take-off.

The participants were told to jump as high as possible in each trial. There were 5 seconds breaks between the CMJs and 1 min breaks between the SPJs. The jump with the highest elevation of the body's COM was chosen for statistical analysis.

The maximum error of the measurement channel is less than 0.5% (Kistler Instruments AG; Winterthur, Switzerland). The total error in the measurement of the peak power output and maximal height of rise of the body COM did not exceed 3.3% and 4.5%, respectively. The maximal error of repeatability, expressed by the coefficient of variability, was 3.0% for the maximal height of rise of the body COM and 3.4% for peak power output.

Muscle strength (peak joint torque)

The peak joint torque (JT) of the flexors and extensors of the elbow, shoulder, hip, knee and trunk were measured under isometric conditions using a special torque meter (Institute of Sport, Poland) type SMS1 (upper extremities) and SMS2 (lower extremities and trunk) [7]. During the measurements of the elbow flexors and extensors, the participant was in a sitting position, with his or her arm and forearm positioned to a 90° angle and placed on the armrest, and with the trunk stabilised. The joint torque of the shoulder flexors and extensors was also measured in a sitting position. The flexion angle was set at 70°, and the extension angle was 50°. The trunk was stabilised with the chest pressed against the backrest. The measurements of the knee flexors and extensors were carried out in a sitting position. The hip and knee joints were bent at 90°. The study participants were stabilised at the level of the anterior superior iliac spines and thighs, with the upper extremities resting on the chest. The participants were lying face down during the measurements of the hip extensors, and face up during the measurement of the hip flexors. The hip joint angle was 90° during both measurements. The maximal extension of the elbow, knee and hip joints was accepted as 0°. For the shoulder joint, the position of the arm along the side was taken as 0°. The axis of rotation during joint torque measurements corresponded to the axis of rotation of the torque meter. Joint torques of the right and left limb were measured separately, with flexion followed each time by extension. The participants were instructed to develop maximal possible contraction.

The total error in the measurement of the maximal joint torque did not exceed 4%. The maximal error of repeatability, expressed by the coefficient of variability, was 4.2%, while for the individual muscle groups it was 1.8% and 2.1% for the knee and hip extensors respectively, 4.9% for the hip flexors, and 6.3% for the shoulder extensors.

The force-velocity (F-v) and power-velocity (P-v) relationships

The force-velocity (*F-v*) and power-velocity (*P–v*) relationships were determined on the basis of the results recorded from a Monark 874 E cycle ergometer (Sweden) connected to a computer, using the MCE 4.0 software package („JBA" Zb. Staniak, Poland). After adjustment of the ergometer saddle and handlebars, each participant performed the tests in a stationary position, without lifting body off the saddle and with feet strapped onto the pedals. Each athlete performed five 10-second tests on a maximal cycle ergometer with an increased external load amounting to 2.5, 5.0, 7.5, 10.0 and 12.5% of body weight (BW), respectively. Two-minute rests were used between the tests. The standard procedure for performing the exercises was followed, and the participants were verbally encouraged to achieve and maintain the maximal pedalling rate as quickly as possible. With the use of MCE, the maximal power output at a given load (P_i; *i* – load value) and velocity (v_i) to be achieved P_i was determined [8].

The total error of the measurement of power output in tests with increasing external loads of 2.5, 5.0, 7.5, 10.0 and 12.5% BW ranged from 1.1 to 1.8%.

Punching bag with in-built strain gauge

The measurements of the punch force were conducted at the Institute of Sport using a versatile Boxing Training Simulator (BTS). The BTS-3 version of the simulator is equipped in a dynamometric punching bag with an in-built strain gauge. The cylindrical punching surface (L) is 0.5 m, and the outer diameter (D) is 0.48 m. The bag is suspended on a set of stabilising ropes. Two signal diodes designed for guiding the sequence of strikes are mounted on an upper cylindrical section of the punching bag (for details see Buśko et al. [9]). The dynamometric punching bag is connected with an external integrated strain gauge amplifier equipped with strain gauge bridge power supply sub-assemblies, signal conditioning sub-assemblies, an analogue-to-digital converter, and a USB interface to connect with a computer. The system is controlled by the BTS specialist software („JBA" Zb. Staniak, Poland). The punching bag measures the resultant reaction force in the plane perpendicular to the cylindrical surface of the punching bag as well as the direction of the force applied during a single punch or kick and the force of consecutive strikes. The punching bag also offers the possibility for a simulated boxing match. When measuring the punching force with the punching bag, the amateur boxers: threw a series of three single straight punches and hooks with the rear and lead hand to develop maximal punching force (MPF); simulate a 60 s (SF60) and 120 s (SF120) fights.

During the simulated boxing fight the athletes, after the light signal, performed punches as fast as possible according to the following random order: yellow light: the straight punch with the lead hand; red light: the straight punch with the rear hand; both lights at the same time: straight punch with any limb or a hook.

Meantime between light signals was 5 seconds. The tests measured the maximal force of straight and hook punches performed with the rear and lead limb.

Since the punching force depends on the thickness of the boxing bandage and gloves [10], all boxers bandaged their limbs with the same bandage and performed punches with the same gloves. The total error in the measurement of the force and time was 0.46% and 1.0%, respectively [9].

Warm-up

Before vertical jump testing, muscle torque measurement and measurements of the strike force, the participants performed a 5-minute warm-up consisting of light exercise (i.e., running, circulation of the arms, hips and trunk, squats followed by stretching exercises). Before evaluation of the force-velocity relationship, the participants performed a 2-minute submaximal warm-up on a cycle ergometer (Monark 874 E, Sweden). They were instructed to cycle at 50-60 rpm and to maintain a power output of approximately 150 W.

Statistical analysis

A repeated measures analysis of variance (ANOVA) was used to compare the study results between the rear limb and lead limb. The significance of differences between means was evaluated post hoc with the Tukey's test. The effect size (ES) in ANOVA was evaluated by eta square and interpreted as follows: $0.01 \le \eta^2 < 0.06$ small, $0.06 \le \eta^2 < 0.14$ medium and $\eta^2 \ge 0.14$ large [11]. Pearson's correlation coefficient was used to evaluate correlations between all indicators. The thresholds used to qualitatively assess the correlations was based on Hopkins [12], using the following criteria: <0.1, trivial; 0.1 to 0.3, small; 0.31 to 0.5, moderate; 0.51 to 0.7, large; 0.71 to 0.9, very large; >0.91 nearly perfect. For the statistical analyses, the value of $\alpha = 0.05$ was considered significant. All computations were performed with Statistica 10 (StatSoft, USA).

RESULTS

The values of peak joint torques for the flexors and extensors of the rear limbs did not differ significantly from the JT values for the lead limbs (Table 1). Table 2 presents the results obtained during the determination of power-velocity profiles. Differences in the height of a rise of the body mass between the SPJ and CMJ jumps were 0.081±0.029 m (Table 3).

The maximal punching force performed with the rear leg during the MPF tests, SF120, SF60 was statistically significantly higher than the punching force performed with the lead limb ($p<0.05$) with the exception of the hook punch in the MPF - the insignificant difference. No statistically significant differences were found in the punching force performed in the MPF tests, SF120 and SF60 for lead limb ($F = 1.6187$, $p = 0.24602$, $\eta^2 = 0.244569$). Statistical significant differences were observed for the rear limb in the force developed in the MPF and SF120 or SF60 ($F = 5.2956$, $p = 0.02701$, $\eta^2 = 0.514356$). The punching force in SF120 and SF60 did not differ significantly (Table 4).

Table 1. Mean values and standard deviations (±) of the peak joint torque [N·m] of the flexors (F) and extensors (E) of the different muscles (variable) of young boxers (n = 6).

Variable		Rear limb	Lead limb
Elbow	F	78.0 ±14.6	75.8 ±13.5
	E	51.7 ±10.4	50.0 ±9.4
Shoulder	F	62.5 ±9.9	57.8 ±9.3
	E	80.8 ±23.32	81.2±24.7
Hip	F	98.7 ±13.5	95.5 ±13.9
	E	427.7 ±161.1	431.5 ±176.1
Knee	F	141.8 ±30.4	129.5 ±33.8
	E	264.8 ±74.5	260.7 ±72.3
Trunk	F	185.7 ±18.7	
	E	514.8 ±151.6	

Table 2. Absolute (P) and relative (P/body mass) power outputs recorded for the external force-velocity relationship (mean values and standard deviations) of young boxers (n = 6).

Load [% BW]	P [W]	P_{max}·BW^{-1}[W·kg^{-1}]	v [rpm]
2.5	353.1 ±46.1	4.73 ±0.20	193.0 ±10.5
5.0	637.7 ±76.3	8.52 ±0.42	173.5 ±8.4
7.5	804.1 ±92.5	10.79 ±0.74	147.1 ±9.5
10.0	850.6 ±106.0	11.41 ±0.91	116.5 ±8.9
12.5	727.2 ±227.2	9.83 ±3.14	80.2 ±25.4
max	860.7 ±95.8	11.56 ±0.92	113.1 ±12.5

Table 3. Mean values and standard deviations (±) of the height of rise of the body mass centre (*h*), peak power output (P_{max}), relative peak power output (P_{max}·$mass^{-1}$) during countermovement jumps (CMJ) and spike jumps (SPJ) on the force plate of young boxers (n = 6).

Jump	P [W]	P_{max}·$mass^{-1}$ [W·kg^{-1}]	h [m]
CMJ	2264.8 ±472.6	29.83 ±7.13	0.430 ±0.050
SPJ	3507.2 ±582.1	45.91 ±6.37	0.511 ±0.068

For the rear limbs, high relationships were found between the JT and the force for individual straight and hook punches with the exception of maximal torques in shoulder and knee flexors and between the JT and the maximum force developed in the SF120 test. Similar relationships were observed for the lead limbs with the exception of the simulated 60-second boxing height, where high relationships occurred only for the hip and trunk flexors and extensors. No relationship was found between JT and the force of punches developed in the 120-second simulation fight test (SF120) (Tables 5 and 6).

Analysis of the linear correlation coefficients showed strong correlations only between the power developed in efforts with varied load (2.5-10.0% BW and P_{max}) in the test performed on a cycle ergometer and punching force developed in the MPF test (both limbs) and SF60 (rear/lead limb). No relationship was found between the punching force developed in the simulated SF120 fight and power developed in the efforts on cycle ergometer performed with a different load. High correlations occurred between the height of rise of the body centre of mass and power of lower limbs developed for the CMJ and SPJ jump and punching force MPF and SF60. The punching force developed in SF120 did not correlate with any indicator (Table 7).

DISCUSSION

Measurements of peak muscle torques, jumping ability and power are commonly used in the sports diagnostics [8, 13-16]. In a study by Loturco et al. [6], Brazilian boxers performed the CMJ jumps to the height of 37.42 ±4.75 cm. Roy et al. [17] documented boxers who jumped to

Table 4. Mean values and standard deviations (±) for the maximal straight and hook punching forces (MPF), maximal punching forces during simulated 60 s (SF60) and 120 s (SF120) fights for lead and rear hand in young boxers (n = 6).

Variables	Rear limb	Lead limb	F	p	η^2
MPF: straight punch [N]	2478.8 ±558.4	1472.8 ±472.6*	96.56482	0.00020	0.950770
MPF: hook punch [N]	2599.7 ±576.3	2192.2 ±888.5	3.5314	0.11900	0.413927
SF120 [N]	1803.3 ±455.0	1209.3 ±251.7*	18.7730	0.00748	0.789677
SF60 [N]	1754.5 ±304.8	1289.0 ±252.6*	14.1153	0.00317	0.562020

* indicates statistically significant difference from the rear limb.

Table 5. The Pearson's linear correlation coefficients between the maximal straight and hook punching forces [N] for lead and rear limb and maximal joint torque [N·m] of the flexors (F) and extensors (E) of the **rear** limb of the different muscles (variables) of young boxers (n = 6).

Variable		Lead straight punch	Lead hook punch	Rear straight punch	Rear hook punch	Lead SF120	Rear SF120	Lead SF60	Rear SF60
Elbow	F	0.57	0.67	0.90*	0.54	0.51	–0.09	0.35	0.47
	E	0.26	0.44	0.76	0.29	0.40	–0.34	0.53	0.62
Shoulder	F	0.16	0.59	0.39	0.20	–0.17	–0.64	0.42	0.77
	E	0.56	0.96*	0.74	0.68	0.03	–0.36	0.03	0.41
Hip	F	0.33	0.64	0.43	0.21	0.09	–0.13	–0.03	0.25
	E	0.85*	0.76	0.96*	0.86*	0.54	0.09	0.31	0.42
Knee	F	0.76	0.92*	0.78	0.84*	0.11	–0.29	0.34	0.67
	E	0.56	0.79	0.91*	0.66	0.31	–0.33	0.39	0.62
Trunk	F	0.84*	0.42	0.90*	0.73	0.76	0.26	0.69	0.60
	E	0.86*	0.88*	0.96*	0.89*	0.41	–0.07	0.37	0.58

*p<0.05

Table 6. The Pearson's linear correlation coefficients between the maximal straight and hook punching forces [N] for lead and rear limb and maximal joint torque [N·m] of the flexors (F) and extensors (E) of the **lead** limb of the different muscles (variable) of young boxers (n = 6).

Variable		Lead straight punch	Lead hook punch	Rear straight punch	Rear hook punch	Lead SF120	Rear SF120	Lead SF60	Rear SF60
Elbow	F	0.61	0.73	0.86*	0.66	0.43	–0.04	0.14	0.29
	E	0.52	0.61	0.89*	0.49	0.53	–0.12	0.43	0.53
Shoulder	F	0.34	0.80	0.52	0.60	–0.30	–0.73	0.30	0.71
	E	0.63	0.94*	0.74	0.70	0.12	–0.20	–0.04	0.29
Hip	F	–0.04	0.33	0.13	–0.18	–0.08	–0.32	0.12	0.35
	E	0.92*	0.69	0.93*	0.86*	0.64	0.28	0.30	0.35
Knee	F	0.49	0.39	0.52	0.53	0.14	–0.30	0.77	0.88*
	E	0.65	0.80	0.93*	0.75	0.31	–0.35	0.54	0.76
Trunk	F	0.84*	0.42	0.90*	0.73	0.76	0.26	0.69	0.60
	E	0.86*	0.88*	0.96*	0.89*	0.41	–0.07	0.37	0.58

*p<0.05

the jump height of 37.31 ±4.28 cm. In the present study, boxers jumped higher. Compared to the findings published by other authors, the measurement methods should be taken into consideration. In the present study, the height of the rise of the centre of mass was calculated from the ground reaction forces while in the studies of the above-cited authors, this value was obtained based on the flight time.

The sum of peak joint torques for 10 muscle groups studied in boxers was 3088.5 ±760.7 Nm and was much greater than in the study published by Janiak and Krawczyk [18], where it was 2439 ±549 Nm. In the present study, no significant differences were found in the values of joint torques between rear and lead limbs although the punching force for the rear limb was greater than the force for the lead limb. There is only one study in the literature that describes the determination of F-v profiles in boxers [14]. Peak power developed during the determination of F-v profiles was 910 ±138 W (11.68 ±1.77 W·kg^{-1}) [14]. A study by Buśko and Wit [19] described the relationship of F-v in karatekas. Peak power in karate athletes was 11.67 ±0.87 W·kg^{-1}. The peak power developed by boxers in the present study (11.56 ±0.92 W·kg^{-1}) was similar to the literature data for boxers and karatekas.

Table 7. Linear correlation coefficients between maximal punching force and power output (P) measured in F-v relationships with an increasing external load amounting to 2.5, 5.0, 7.5, 10.0 and 12.5% BW, peak power output (P_{max}) and jump height (h) measured in the CMJ and SPJ jump in young boxers (n = 6).

Variable-	[% BW]	Lead straight punch	Lead hook punch	Rear straight punch	Rear hook punch	Lead SF120	Rear SF120	Lead SF60	Rear SF60
P [W]	2.5	0.95*	0.68	0.95*	0.89*	0.54	−0.17	0.54	0.65
v [rpm]		0.97*	0.85*	0.92*	0.97*	0.34	−0.31	0.30	0.53
P [W]	5.0	0.99*	0.78	0.99*	0.86*	0.54	−0.21	0.55	0.73
v [rpm]		0.76	0.82*	0.73	0.56	0.28	−0.31	0.27	0.57
P [W]	7.5	0.98*	0.83*	0.98*	0.82*	0.52	−0.18	0.43	0.64
v [rpm]		0.34	0.65	0.28	0.22	−0.09	−0.25	−0.25	0.07
P [W]	10.0	0.96*	0.79	0.97*	0.76	0.58	−0.10	0.43	0.62
v [rpm]		0.43	0.63	0.41	0.23	0.11	−0.11	−0.12	0.14
P [W]	12.5	0.35	0.41	0.41	0.13	0.38	0.36	−0.22	−0.13
v [rpm]		0.05	0.23	0.09	−0.13	0.15	0.37	−0.43	−0.36
P [W]	max	0.92*	0.78	0.93*	0.74	0.57	0.01	0.28	0.45
v [rpm]		0.66	0.69	0.64	0.42	0.25	−0.37	0.42	0.70
PmaxCMJ [W]		0.51	0.38	0.54	0.20	0.38	−0.27	0.72	0.85*
hCMJ	[m]	0.80	0.84*	0.74	0.64	0.20	−0.50	0.40	0.73
PmaxSPJ [W]		0.72	0.69	0.72	0.45	0.38	−0.27	0.46	0.71
hSPJ	[m]	0.87*	0.92*	0.82*	0.76	0.28	−0.27	0.12	0.43

*p<0.05

Boxers used upper limbs to perform punches during the fight. The value of the punching force depends on the measurement method, technical skill level of the athlete, type of punch (straight/hook), limb that performs the punch (dominant/non-dominant, lead/rear limb), position of the wrist (straight/bent) or type of boxing gloves [5, 10, 20-24]. Atha et al. [25] documented a force peak of 4096 N. A study published by Waliko [21] recorded values of punching force ranging from 1990 to 4741 N. Depending on the position of the wrist, mean value of force was 3671 ±814 (stiff wrist) and 2775 ±780 N (bend wrist). Smith at al. [5] found that the punching force decreased with the skill level. The force of the straight punch performed with the rear limb was 4800 ±227 N in the best boxers, 3722 ±133 N in the medium-class boxers and 2381±116 N in beginner boxers, with 2847 ±225 N, 2283 ±126 N and 1604 ±97 N, respectively, for the lead hand. Joch [26] also observed a reduction in the value of punching force with the class of the athletes from 3453 N to 2932 N. The study by Karpiłowski et al. [27] demonstrated that maximal punching force was 2697 N. In a study by the same authors [20], the punching force for the lead hand was 1324 N and for the rear hand 2021 N. In our study, measurements were performed using the boxing ergometer similar to the ergometer used in studies by Karpiłowski et al. [20, 27]. The results obtained in our study are consistent with the findings presented by Karpiłowski et al. [20, 27] and Smith at al. [5] for beginner athletes. Smith at al. [5] found that the punching force for the straight punch performed with the rear hand is greater than for the punch performed with the lead hand. The results obtained in our study are also consistent with the data presented by Smith et al. [5], but the statistically significant differences between the limbs were not observed for the hook. The greater asymmetry observed in the straight punching force (−40.8%) compared to the difference between the strength of the hook performed with the rear and lead limb (−16.7%) may result from the fact that a hook, compared to MPF, is performed using „the entire body". This is consistent with the results documented by Kornecki et al. [28], who found that the punch performed by the rear hand is the most effective if the boxer utilises the „kinetic energy of the rotational body movement" around the transverse axis that passes through the hip joints.

This study attempted to find the relationship between peak torque of the main muscle groups and the punching force for the punches performed by boxers to a boxing training simulator. For the rear limbs, high relationships were found between the JT and the force for individual straight and hook punches with the exception of maximal torques in shoulder and knee flexors and between the JT and the maximum force developed in the SF120 test. Similar relationships were observed for the lead limbs with the exception of the simulated 60-second boxing height, where high relationships occurred only for the hip and trunk flexors and extensors. No relationship was found between JT and the force of punches developed in the 120-second simulation fight test (SF120). Strong correlations occurred only between the power developed for the efforts with varied load (2.5%-10.0% BW and P_{max}) in the test performed on a cycle ergometer and punching force developed in the MPF test (both limbs) and SF60 (rear/lead limb). No relationship was found between the punching force developed in the simulated SF120 fight and power developed in the efforts on cycle ergometer performed with a different load.

High correlations occurred between the height of rise of the body centre of mass and power of lower limbs developed for the CMJ and SPJ jump and punching force MPF and SF60. This is consistent with the findings presented by Loturco et al. [6], where the relationship was found between the jump height (static jump) and the CMJ jump and punch strength (r = 0.67÷0.80). The punching force developed in SF120 did not correlate with any indicator. In a study by Karpiłowski et al. [2], the strongest correlations occurred between maximal torques in trunk flexors and the force of punch with the rear (0.475) and lead (0.571) limb in athletes from the national boxing team. The substantial effect during punching and kicks with the rear limb was from the shoulder flexors (0.486), whereas lower effect was observed for the elbow flexors (0.263) and the flexors (0.320) and extensors (0.267) of the knee joint. The force of punches with the left limb was less correlated with forces of muscles in static conditions. The values of the linear correlation coefficients in this study were much higher. This might result from the fact that in a study by Karpiłowski et al. [2] the force was recorded during the simulated three-minute fight using the boxing training simulator. The results of our studies show that, with elongation of the duration of the boxing fight, the relationships between the punching force and peak joint torques decreases or the relationship becomes negative (Test SF120, rear limb) although no statistically significant differences were found between the punching force developed in the simulated fights with duration of 60 s and 120 s. The results of the study are likely to confirm the observations of the coaches that the punches with the rear and lead limbs are performed in a different manner and engage different muscle groups.

CONCLUSIONS

The results obtained in this study lead to the following practical applications: 1) lack of differences in the values of forces between the rear and lead limbs and finding correlations between the punching force and the joint torques are likely to show that the punching force may depend on other factors, e.g. technique; 2) special measurements of the punching force over the training process using the punching bag may be replaced by other tests, such as e.g. jump tests or performance of short-term maximum exercise on a cycle ergometer with the load of 2.5% and 5% of body mass and allows for the choice of adequate methods and training exercises (e.g. plyometric training); 3) the use of all these methods provides more information for planning of optimal training control.

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Cite this article as: Buśko K. Biomechanical characteristics of amateur boxers. Arch Budo 2019; 15: 23-31