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Measuring the force of punches and kicks among combat sport athletes using a modified punching bag with an embedded accelerometer

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The main aim of the study was to design a new system to measure punching and kicking forces as well as reaction times in combat sport athletes. In addition, the study examined whether there were any intergender differences in the force of punches thrown by boxers and kicking forces delivered by taekwondo athletes. Boxers (male, $n = 13$; female, $n = 7$) were examined for the force of single straight punches and taekwondo athletes (male, $n = 14$; female, $n = 14$) for force of single Apdolio and Dwit Chagi kicks. The punching bag was equipped with acceleration transducers and gyroscopes embedded in a cylinder covered with a layer to absorb shock as well as a set of colour signal diodes. Value of the punching bag's acceleration was used for calculating: strike force; the punching location on the bag; and time of a strike. The relative error of force calculation was 3%; the relative error in acceleration measurement was less than 1%. The force of a straight rear-hand punch was greater than the force of a lead-hand punch among male and female boxers. The force of Apdolio kick delivered with a rear leg was greater compared to a lead leg among female and male taekwondo athletes. Significant gender differences were noticed in the force in both types of kicks. In boxers, intergender differences were reported only for the force of a punch thrown with the rear hand. Based on these findings, it was concluded that the modified punching bag is a good diagnostic tool for combat sports.

Key words: *accelerometric boxing training simulators, boxing, force, kick, punch, taekwondo*

1. Introduction

In combat sports, tournament results are determined by a number of interrelated factors: motor characteristics, technique, tactics, psychological features of the athletes, and the refereeing method [5], [6], [14], [15], [18]. The force of a punch or a kick delivered to a punching bag is a crucial element of special fitness [3], [16], [17]. Smith et al. [16] have proven that the force of the rear-hand punch is greater than the force of the lead-hand punch in boxers and that the power of the punching force is dependent on the athletes' skills. Similar assertions can be made about the kicking force in taekwondo. In literature related to the subject, only a small number of studies exist that compare punching and kicking forces between female and male athletes [8]. Several systems to measure strike force have been described in the literature: a water-filled heavy bag [11], force plate [10], strain gauge-based measuring systems [5], [7], and an accelerometer-based measuring system [9]. Consisting of a punching bag with an embedded strain gauge, the BTS-3

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boxing training simulator system [7] formerly utilised at the Institute of Sport in Warsaw did not fully meet the diagnostic expectations of boxing and taekwondo; hence, the development of a new boxing training simulator that would meet the requirements of both sports disciplines was necessary.

The main aim of the study was to design a new system to measure punching and kicking forces as well as reaction times in combat sport athletes. In addition, the study examined whether there were any intergender differences in the force of punches thrown by boxers and kicking forces delivered by taekwondo athletes.

2. Materials and methods

Ethical approval for this study was provided by the Local Ethical Committee at the Institute of Sport in Warsaw, Poland. A written informed consent was obtained from participants or their parents if a participant was under 18 years of age. The study was performed in accordance with the Declaration of Helsinki.

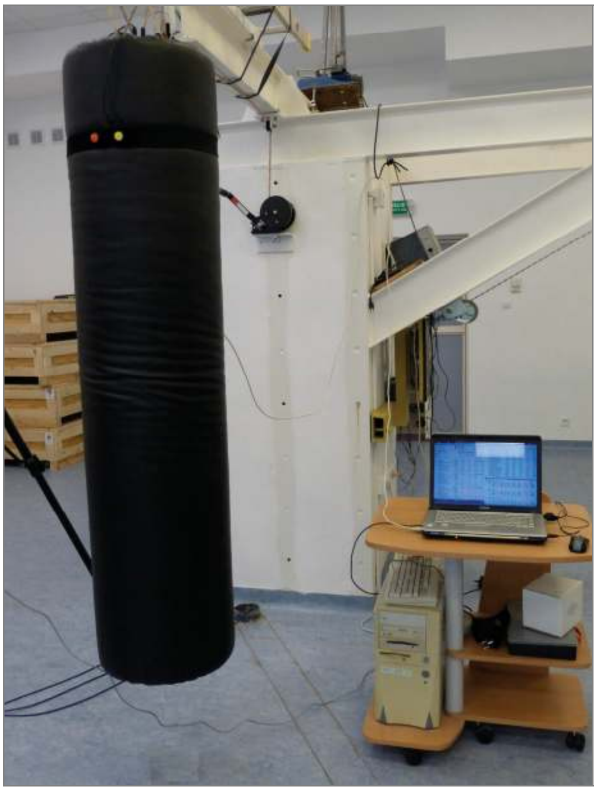

Fig. 1. BTS-4AP-2K dynamometric punching bag with an embedded accelerometer

Table 1. Mean values (± SD) of anthropometric characteristics of participants

Groups	Gender	Age [years]	Body mass [kg]	Body height [cm]	Training experience [years]
Boxers, *n* = 7	♀	17.0 ± 1.1	68.9 ± 12.4	165.9 ± 3.8	2.6 ± 1.5
Boxers, *n* = 13	♂	17.1 ± 1.5	68.7 ± 12.0	175.5 ± 5.3	3.1 ± 1.6
Taekwondo, *n* = 14	♀	18.7 ± 3.1	59.9 ± 8.1	171.3 ± 7.6	7.1 ± 4.5
Taekwondo, *n* = 14	♂	17.6 ± 2.7	67.0 ± 8.9	179.4 ± 6.7	8.1 ± 2.8

Legend: ♀ – female, ♂ – male.

A total of 14 female and 14 male Olympic taekwondo (WTF) athletes as well as 7 female and 13 male boxers participated in the study. The characteristics of the study participants are shown in Table 1.

Punching bag with an embedded accelerometer

In 2013, a diagnostic system BTS-4AP-2K was designed. Its key element comprises a dynamometric punching bag with an embedded accelerometer (Fig. 1). It is a long, cylinder-shaped bag (L = 1.8 m; D = 0.42 m; mass = 41 kg) consisting of a stiff inner cylinder and an outer layer to absorb shock.

Throughout its length, the body of the dynamometric punching bag is solid with a stiff core. The bag's centre of mass is at the midpoint of its height. For measurement purposes, two tri-axial accelerometers mounted on the edge surfaces of the punching bag's inner cylinder base were applied. In addition, using the new BTS6v0 software provides the opportunity to measure strike force in three different dimensions, to compute the location of the point at which the strike is delivered, and to measure the energy of the strike. The use of four signal diodes enabled tests to be conducted in which strikes could be executed with both upper and lower limbs and at different heights permitted in a given sports discipline. After the test is completed, the software generates a standard worksheet that contains measurement results as well as the calculations and analyses of the recorded trials. The worksheet presents the statistics of maximal, absolute, and relative forces of strikes delivered. It also presents force impulse and reaction time for a left and right limb separately as well as for consecutive strikes. The numerical scores of measurements and analyses are available in a text format (ASCII export) for further processing with specialised statistical software.

The general mathematical model of the dynamometric punching bag

Assuming that a punching bag is a solid object, the general vector equations of the equilibrium of forces and the moments of forces acting on the bag are given by formulas (1) and (2)

$$F_r + Q + F_h + m * a = 0, \quad (1)$$

$$F_r * r + \varepsilon * J = 0, \quad (2)$$

where

F_r – punching bag's impact reaction force,

F_h – reaction force of suspension ropes,

Q – punching bag's weight force,

M_h – ropes reaction moment,

r – distance of the bag's reaction force from the bag's centre of mass,

m – the mass of the bag,

J – moments of inertia against the bag's centre of mass,

a – acceleration of the punching bag's centre of mass,

ε – angular acceleration of the punching bag's body against the bag's centre of mass.

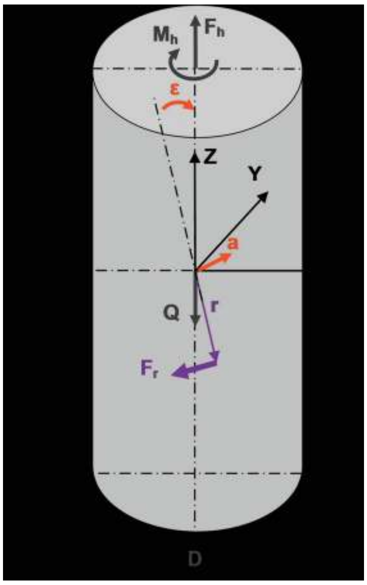

Fig. 2. A diagram showing forces and accelerations acting on the dynamometric punching bag. Legend: F_r – punching bag's impact reaction force, F_h – reaction force of suspension ropes, Q – punching bag's weight force, M_h – ropes reaction moment, r – distance of the bag's reaction force from the bag's centre of mass, a – acceleration of the punching bag's centre of mass, ε – angular acceleration of the punching bag's body against the bag's centre of mass, L – distance of the punching bag's edge acceleration measurement points, D – outer diameter

By applying appropriate measuring methods and assuming certain reductions in the general mathematical model, it is possible to take direct measurements or calculate the value of the force of strikes delivered to the dynamometric punching bag (Fig. 2).

The accuracy of measurements and computations of strike force depends on the methods applied for measuring force and acceleration as well as reductions used in the general model. The physical and chemical properties of the layer indispensable for absorbing blows delivered with upper and lower limbs have a significant influence on the measurement results as well. The stiffness of the layer that absorbed the shock, the degree of energy dissipation, and the changes of the properties due to the ageing of materials determine the measurement results regardless of the type and accuracy of measuring transducers used.

The method of measuring strike force delivered to a punching bag with an embedded accelerometer

In order to obtain the results of strike force measurements comparable with the previously applied measuring method, a simplified computational model for a planar force system (Fig. 3) was applied in which it was assumed that

– a strike force component perpendicular to the punching bag's cylindrical surface will be calculated,
– a strike is momentary, and the displacements of the punching bag's centre of mass until its maximal acceleration is achieved (the punching bag's maximum reaction force to the strike) are negligibly small from the point of view of the accuracy of calculating the force,
– suspension force counterbalances the weight of the punching bag.

Described with equations (3) and (4) below, a two-dimensional model of the equilibrium of forces and the moments of forces acting on the punching bag was used

$$F_r * r + \varepsilon_y * J_y = 0, \quad (3)$$

$$F_r + m * a = 0, \quad (4)$$

where

F_r – punching bag's strike reaction force,

r – distance of the punching bag's reaction force from the punching bag's centre of mass,

ε_y – angular acceleration of the punching bag's body against the punching bag's centre of mass in the y-axis,

J_y – moments of inertia against the punching bag's centre of mass,

m – the mass of the punching bag,

a – acceleration of the punching bag's centre of mass.

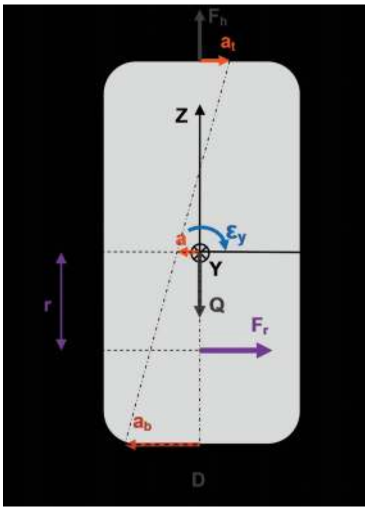

Fig. 3. A simplified, two-dimensional diagram of measured accelerations and forces acting on the dynamometric punching bag having an embedded accelerometer. Legend: F_r – punching bag's strike reaction force, r – distance of the punching bag's reaction force from the punching bag's centre of mass, ε_y – angular acceleration of the punching bag's body against the punching bag's centre of mass in the y-axis, a – acceleration of the punching bag's centre of mass, a_t – acceleration of the punching bag's upper edge, a_b – acceleration of the punching bag's lower edge, L – distance of the punching bag's edge acceleration measurement points, F_h – reaction force of suspension ropes, Q – punching bag's weight force, D – outer diameter

The acceleration of movement of the punching bag's centre of mass (a) and the angular acceleration (ε_y) of rotation about the y-axis are calculated on the basis of the measurement results of the horizontal components of the tri-axial acceleration of the punching bag's upper and lower edges (a_t and a_b) according to formulas (5) and (6).

$$a = 0.5 * (a_t + a_b), \quad (5)$$

$$\varepsilon_y = (a_b - a_t)/L, \quad (6)$$

where

a – acceleration of the punching bag's centre of mass,

a_t – acceleration of the punching bag's upper edge,

a_b – acceleration of the punching bag's lower edge,

ε_y – angular acceleration of the punching bag's body about the y-axis,

L – distance of the punching bag's edge acceleration measurement points.

The strike force is calculated according to the following formula

$$F_r = 0.5 * m * (a_t + a_b). \quad (7)$$

The point at which the strike force is applied to the punching bag's centre of mass is computed using the formula

$$r = J_y * (a_b - a_t)/(L * F_r). \quad (8)$$

The method of executing and measuring test strikes with a dynamometric impact hammer

In order to verify the method for measuring and calculating force used for a punching bag, measurements of strike forces delivered with a special dynamometric impact hammer equipped with a strain gauge-based force transducer were performed (Fig. 4). The face of the impact hammer was affixed with a single-component force measurement transducer equipped with a light metal spherical cap through which strike force was exerted onto the dynamometric punching bag. The outer diameter (D_z) of the impact hammer's spherical cap was 64 mm and the radius (r) was 70 mm (Fig. 5). The impact hammer was suspended on two parallel ropes at points equidistant from the impact hammer's centre of mass. The impact hammer's longitudinal axis was thus perpendicular to the punching bag's cylindrical surface during impact. Prior to executing a strike, the rope-suspended impact hammer was pulled back away from the punching bag. Next, initial velocity was given to the impact hammer, which was released freely towards the punching bag. The dynamometric punching bag received from five to eight strikes against different sections of the punching bag's available striking surface. The hammer's force of impact with the punching bag was determined by means of the measuring systems affixed to the impact hammer and the punching bag.

Fig. 4. The view of the dynamometric punching bag having an embedded accelerometer when delivering test strike

The force-measuring chains, with which both the impact hammer and the dynamometric punching bag having the embedded strain gauge were furnished, consisted of a force transducer with own vibrational frequency of 160 Hz. The measuring system of the strain gauge amplifier was equipped with a first-order low-pass filter with a cutoff frequency of 300 Hz. Forces were sampled with a 12-bit analogue-to-digital converter with a sampling rate of 500 Hz. The measurement error of force is less than 1%.

Fig. 5. The view of the impact hammer's spherical face used to deliver test strikes

The acceleration-measuring chains of the dynamometric punching bag having an embedded accelerometer were equipped with factory-fitted anti-aliasing filters of 780 Hz. Acceleration was sampled at 1000 Hz. The results of acceleration measurements were "smoothed out" with a digital low-pass filter with a cutoff frequency of 200 Hz. The measurement error of acceleration is less than 1%.

Measuring the force of punches and kicks delivered both by boxers and by taekwondo athletes

When measuring punching and kicking force with the punching bag

- the boxers threw a series of three single straight punches and hooks with the rear hand and lead hand to develop maximal punching force,
- the taekwondo athletes delivered three Apdolio kicks and three Dwit Chagi kicks with the lead leg and rear leg to develop maximal kick force.

Since bandage thickness and type of boxing gloves affect punch force [13], all boxers covered their hands with the same type of bandage and threw punches using the same boxing gloves.

All measurements were performed in the morning.

3. Statistical analysis

A repeated measures analysis of variance (ANOVA) was used to compare the study results between the rear limb and lead limb. In order to compare the results between females and males, a single factor ANOVA was performed. The significance of differences between means was assessed post hoc with Tukey's test. The effect size (ES) in ANOVA was assessed 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. Pearson's correlation was used to find the relationship between the force recorded with a strain gauge-based impact hammer and the force calculated based on the accelerations of the punching bag with an embedded accelerometer. For the statistical analyses the value of $\alpha = 0.05$ was considered significant. All computations were performed with STATISTICA software™ (v. 10.0, StatSoft, USA).

4. Results

Figure 6 presents the measurement results of test strikes delivered with the impact hammer to the punching bag having an embedded accelerometer of the BTS-4AP-2K system.

Figure 7 shows relationships between maximal test strike forces recorded with the measuring systems of the impact hammer and the punching bag having an embedded accelerometer of the BTS-4AP-2K system.

Figure 8 presents the relationship between the real strike height measured and the height of strike calculated on the basis of the results measured with the BTS-4AP-2K system.

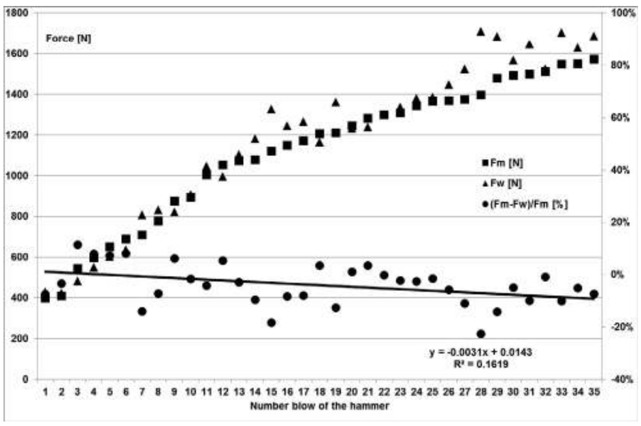

Fig. 6. Graph showing maximal values of the force of test strikes as a function of subsequent strikes; F_m – force of impact of the hammer, F_w – force measured with BTS-4AP-2K

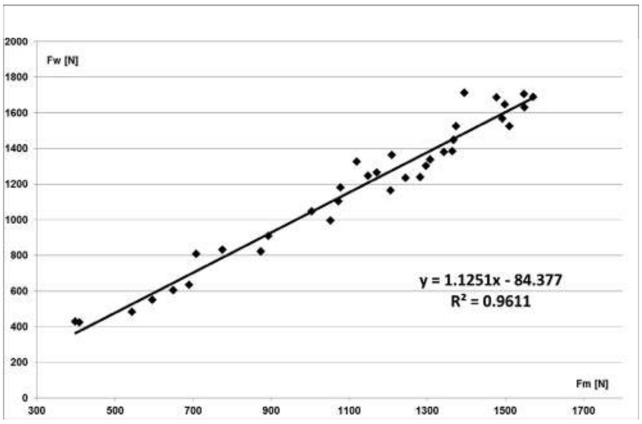

Fig. 7. The relationship between the force of impact (F_m) of the hammer and the force measured (F_w) with the BTS-4AP-2K system

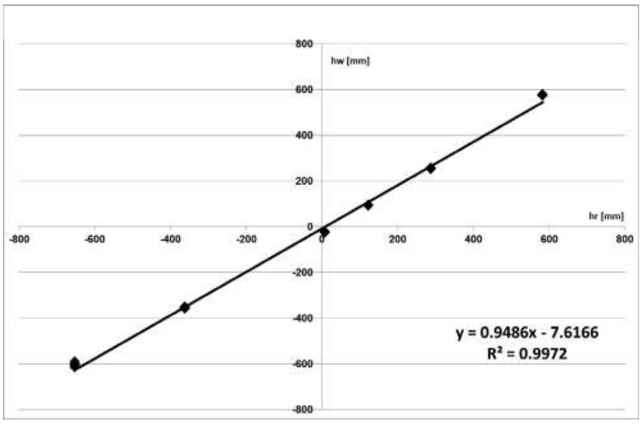

Fig. 8. The relationship between the real strike height measured (h_r) and the height of strike calculated (h_w) on the basis of the results measured with the BTS-4AP-2K system

The accelerometer-based method results show that the mean relative error of force calculation amounts to 3%. The measurement error of acceleration is less than 1%. The mean relative error of calculation of the punching place on the boxing bag is 2%. The accelerometer-based detectors work in frequency bandwidth of maximum 1000 Hz. The measurement data of the accelerometer-based system are filtered with a low-pass filter (200 Hz) in order to eliminate high peaks detected.

Table 2 presents mean values of the maximal force of a straight lead-hand and rear-hand punch as well as reaction times in boxers. The force of straight rear-hand punches among boxers was significantly greater compared to the force of lead-hand punches thrown by females ($F_{1.6}$ = 10.59; P = 0.0174; η^2 = 0.638) and males alike ($F_{1.12}$ = 69.68; P < 0.001; η^2 = 0.8531). Significant differences in reaction time for lead-hand and rear-hand punches were reported only in females ($F_{1.6}$ = 30.27; P = 0.0015; η^2 = 0.835). Inter-gender differences were observed only for the force ($F_{1.18}$ = 4.48; P = 0.0484; η^2 = 0.199) and the reaction time ($F_{1.18}$ = 12.09; P = 0.0027; η^2 = 0.402) for the rear-hand punch.

Mean values of the maximal force of Apdolio and Dwit Chagi kicks as well as reaction times in taekwondo athletes are shownin Tables 3 and 4, respectively. The force of the Apdolio kicks delivered with the rear leg by taekwondo athletes was significantly greater compared to the force of lead kicks delivered by females ($F_{1.13}$ = 58.69; P < 0.001; η^2 = 0.819) and males alike ($F_{1.13}$ = 68.15; P < 0.001; η^2 = 0.840).

Table 2. Mean values (± SD) the maximal straight punch forces (F_{max}) and reaction time for lead- and rear-hand in boxers

Gender	Lead hand		Rear hand	
	F_{max} [N]	Reaction time [s]	F_{max} [N]	Reaction time [s]
♀, n = 7	848.4 ± 218.5	0.512 ± 0.066	1170.7 ± 165.3#	0.619 ± 0.025#
♂, n = 13	1102.9 ± 430.7	0.496 ± 0.112	1592.5 ± 507.1*#	0.528 ± 0.068*

Legend: ♀ – female, ♂ – male; * – mean values which differ significantly compared to females, P < 0.05, P < 0.05; # – mean values which differ significantly compared to lead-hand punches, P < 0.05.

Table 3. Mean values (± SD) of maximal kick forces of Apdolio (F_{max}) and reaction time for lead- and rear-leg kicks among taekwondo athletes

Gender	Lead leg		Rear leg	
	F_{max} [N]	Reaction time [s]	F_{max} [N]	Reaction time [s]
♀, n = 14	965.3 ± 234.1	0.718 ± 0.084	1511.6 ± 271.0#	0.682 ± 0.058
♂, n = 14	1206.7 ± 239.5*	0.644 ± 0.064*	2072.3 ± 472.2*#	0.631 ± 0.066*

Legend: ♀ – female, ♂ – male; * – mean values which differ significantly compared to female, P < 0.05, P < 0.05; # – mean values which differ significantly compared to lead hand, P < 0.05.

Table 4. Mean values (± SD) the maximal kick forces of Dwit-chagi (F_{max}) and reaction time for lead- and rear-leg kicks among taekwondo athletes

Gender	Lead leg		Rear leg	
	F_{max} [N]	Reaction time [s]	F_{max} [N]	Reaction time [s]
♀, n = 8	2461.1 ± 494.7	0.671 ± 0.166	2490.3 ± 846.2	0.716 ± 0.075
♂, n = 9	3.514.6 ± 1.190.4*	0.694 ± 0.078	3.426.1 ± 911.0*	0.693 ± 0.080

Legend: ♀ – female, ♂ – male; * – mean values which differ significantly compared to females, $P < 0.05$.

Intergender differences were observed for the Apdolio kick delivered with the rear leg and force ($F_{1.26} = 14.85$; $P < 0.001$; $\eta^2 = 0.3635$) as well as reaction time ($F_{1.26} = 4.73$; $P = 0.0390$; $\eta^2 = 0.154$); the differences were also reported for the lead leg and force ($F_{1.26} = 9.38$; $P = 0.0051$; $\eta^2 = 0.265$) as well as reaction time ($F_{1.26} = 5.54$; $P = 0.0264$; $\eta^2 = 0.176$).

Among taekwondo athletes, the force of the Dwit Chagi rear-leg kick was not significantly different from the force of kicks delivered with the lead leg in females and males alike. Intergender differences were observed only in the force of the Dwit Chagi rear-leg kick ($F_{1.15} = 5.40$; $P = 0.0346$; $\eta^2 = 0.265$) and lead-leg kick ($F_{1.15} = 4.78$; $P = 0.0451$; $\eta^2 = 0.242$).

5. Discussion

The main aim of the study was to design a new device to measure punching and kicking forces in combat sports that could replace the strain gauge-based measurement system used formerly. In the literature, various methods to measure punching and kicking force can be found along with very diverse force values obtained [1], [4], [7], [9]–[11]. Using a water-filled heavy bag, Pieter and Pieter [11] recorded kick forces ranging from 461.8 ± 100.7 N to 661.9 ± 52.7 N. Balius [1] reported mean impact force of nearly 2130 N, while Conkel et al. [4], who used piezoelectric film, measured impact forces up to 470 N. Falco et al. [5] measured the force of Bandal Chagi kicks using piezoelectric pressure sensors mounted on a boxing mannequin and recorded maximal forces of 2089.8 ± 634.7 N with the highest force being 3482 N. On the other hand, Pędzich et al. [10] recorded kick forces on a force plate up to 9015 N. The impact forces of delivered kicks were reported at a broad range of 382 N to 9015 N and depended on the measuring methods adopted and the type of punches and kicks performed [4], [5], [10]–[12], [16], [17]. In boxers, the recorded punching forces ranged from 1990 N to 4741 N [16], [17]. Smith et al. [16] established that the force of a straight rear-hand punch equalled 4800 ± 227 N among elite boxers, 3722 ± 133 N in the intermediate group, and 2381 ± 116 N among novices. Similarly, the punching force for a lead hand were, respectively, 2847 ± 225 N, 2283 ± 126 N, and 1604 ± 97 N. The maximal striking forces recorded by Karpiłowski et al. [7] totalled 2697 N. In our study, the use of acceleration measurement transducers and angular velocity transducers measuring the movement of a dynamometric punching bag enabled the construction of a dynamometric punching bag with a considerably longer cylindrical striking surface (L = 1.8 m) than in the formerly used BTS-3 punching bag (L = 0.5 m) with an embedded strain gauge that was described in the study by Karpiłowski et al. [7]. The use of four signal diodes enabled tests to be conducted in which strikes could be executed with both upper and lower limbs and at different heights permitted in a given sports discipline. The punching forces recorded with our punching bag having an embedded accelerometer oscillated between 500 N and 2276 N among the group of boxers; the kick forces (Dwit Chagi) among taekwondo athletes ranged from 1576 N to 5315 N. The values of force we recorded for boxers corresponded to the results obtained by Karpiłowski [7] and Smith et al. [16] for novice athletes. Smith et al. [16] established that the force of a straight rear-hand punch was greater than the force of a straight punch thrown with a lead hand. The results obtained by us corresponded to the data collected by Smith et al. [16]. Furthermore, the results we recorded with our new punching bag having an embedded accelerometer were similar to the results produced by the BTS-3 strain gauge-based punching bag, thus enabling the comparison of the results obtained in earlier studies using the punching bag having an embedded strain gauge [2]. Li et al. [8] observed roundhouse kick that had forces of 2940 N for males and 2401 N for females. In our study, intergender differences were observed among taekwondo athletes for both types of kicks delivered with a rear and lead leg, which is consistent with the results obtained by Li et al. [8]. In the case of boxers, significant intergender differences occurred for the rear hand. Conversely, for the lead-hand punch, the differences were statistically insignificant. Moreover, intensity of training can be controlled more rigorously due to the possibility of setting, e.g., time intervals between consecutive strikes or the sequences of strikes delivered. The bigger punching bag is equipped with more versatile software, which makes it a good tool for practical application in combat sport training.

6. Conclusions

Due to new construction solutions, the new boxing training simulator system BTS-4AP-2K is sufficiently functional to be used for diagnostics in taekwondo while at the same time offering greater diagnostic capabilities for boxing (punches aimed at the head and chest). The results obtained have demonstrated that intergender differences occurred in the force of Apdolio and Dwit Chagi kicks. In the case of straight punches thrown by boxers, intergender differences were noticed only for the rear hand.

The punching bag having an embedded accelerometer is equipped with more versatile software, thus making the system a good tool for practical application in combat sport training.

Acknowledgments

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