ORIGINAL ARTICLE

The objective assessment of striking force in combat sports using sport-specific measurement devices – – a review

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

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Abstract

Background and Study Aim: Throughout the literature, numerous measurement systems have been designed aiming to provide a point of reference to scale the intrinsic performance of combat sports athletes. However, magnitude of force exerted by the athletes varied greatly between studies and it is difficult to find consistencies in research in this area. Thus, the purpose of this study was to review recent research regarding the striking (punching and kicking) forces and usefulness of sport-specific measurement devices exclusively dedicated for combat sports athletes.

Material and Methods: The search of following databases: SPORTDiscus, Scopus, Google Scholar, PubMed and Springer were conducted using different combination of terms: (training simulator OR training device OR device) AND (combat sports OR martial arts OR judo OR karate OR taekwondo OR boxing OR mixed martial arts OR Thai chi).

Results: The literature search retrieved a total of 4028 and 9 of them met inclusion criteria. The target-based measurement devices: punching bags, manikins and impact platform, as well as wireless in-glove systems were used. Most of the included studies showed significant influence of gender, level of expertise and the striking technique on the impact forces associated with punching and kicking.

Conclusions: There are plenty of valid, accurate and reliable devices which opens up new possibilities in enhancing combat sport training and performance. Unfortunately, because of the large methodological and technological diversity, the results obtained by different studies cannot be directly compared. The future research perspectives should include the evaluation of diverse groups of athletes across different force measurement devices.

Key words: boxing manikin • force sensors • impact force • kicking • martial arts • punching • punching bag • strain gauge

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Straight punch – is also known as „cross", because during punch the blow crosses over the leading arm. This is a punch thrown with the dominant hand the instant an opponent leads with his opposite hand.

Hook punch – typical boxing punch, performed by turning the core muscles and back, thereby swinging the arm, which is bent at an angle near or at 90 degrees, in a horizontal arc into the opponent. A hook is usually aimed at the jaw.

Front kick – in martial arts is a kick executed by lifting the knee straight forward, while keeping the foot and shin either hanging freely or pulled to the hip, and then straightening the leg in front of the practitioner and striking the target area.

Apdolio – is a typical taekwondo kick. Also known as „fast kick". During punch feet goes for 45' down, knee is raised higher than feet, then leg straightens.

Dwit Chagi – is a typical taekwondo kick. From the standing position, one lifts up the kicking leg and stretches it backward to deliver a kick. The back is sole is used for the kick.

Yop Chagi – is a typical taekwondo kick. One lifts up the kicking leg, folding the knee, and then stretches the folded knee as he or she turns the body in the opposite direction to the target and kick the target with the back sole of foot.

Bandal Chagui – is a typical taekwondo kick. The fore sole or the foot back delivers a kick by making a slant circle of movement.

Impact force – when one thing is going to hit another one, the impact force interacts on them.

Calibration - is the method by which the voltage obtained in the tensor amplifier, which is connected to the sensor, relates to the force that is acting on the sensor, expressed in kilos force or in Newtons.

Piezoelectric sensor – is a device that uses the piezoelectric effect to measure changes in pressure, acceleration, temperature, strain, or force by converting them to an electrical charge.

INTRODUCTION

One of the fundamental aim in sport is to maximize athletes' performance. Research and innovation technology provide an increasing number of information about motor characteristics, technique, tactics and psychological features of the athletes, supporting thereby physical training [1, 2].

In the combat sports, such as boxing, karate, taekwondo, etc., results are determined by a number of interrelated factors like strength, coordination, speed and stamina [3-6]. Among various components the striking force is considered a major determinant of a fighter's victory [7-11]. Generally, striking aims to impose physical damage, develop tactical advantage, and score points against an opponent [4, 9].

Several authors have highlighted that the striking forces can be measured and analysed to provide diagnostic, programming and prognostic information for talent identification or team selection [4, 12, 11, 13]. Changes in striking force, as one of the key indicators of performance [7, 14, 15], may enhance designing of accurate strength and conditioning interventions [16, 17, 15]. Furthermore, the measurement and analysis of striking forces can serve as an indicator for categorizing combat sport athletes according to their punching forces [11, 4].

Throughout the literature, numerous measurement systems have been designed aiming to provide a point of reference to scale the intrinsic performance of combat sports athletes. However, magnitude of force exerted by the athletes varied greatly between studies and it is difficult to find consistencies in research in this area [16, 18, 8, 14, 1, 5]. Several authors have raised the issue of discrepancy in reported values of observed variables [14, 15, 5]. In the literature there are several reviews concerning striking force in combat sports [19, 11, 13]. In most recent review [13], authors highlighted that striking actions must be evaluated in the context of a particular combat system. They reported, that the measurement of upper limb strikes lacks unification in terms of the methodology and equipment used. They also concluded that most of the reviewed studies were using their measures without justification of evaluated parameters (indicators). Although this review contributed to systematizing the state of the art in this area, it analysed only upper limb strike actions and it lacks detail analysis and description of the measurement equipment.

Considering all the above, the purpose of this study was to review recent research regarding the striking (punching and kicking) forces and usefulness of sport-specific measurement devices exclusively dedicated for combat sports athletes.

MATERIAL AND METHODS

Search strategy

Publications search was time restricted from year 2000 to 2021. The search of following databases: SPORTDiscus, Scopus, Google Scholar, PubMed and Springer were conducted using different combination of terms: (training simulator OR training device OR device) AND (combat sports OR martial arts OR judo OR karate OR taekwondo OR boxing OR mixed martial arts OR Thai chi). Furthermore, manual searches based on the references listed in the reviewed articles were performed to complete the search. Literature search was completed in March, 2021. Early screening of the articles based on the titles and abstracts was performed by two authors BG and AB. Full-text articles were independently assessed by authors AA and BB.

Eligibility criteria

Studies were chosen under following inclusion criteria: (1) full-text was available in English, (2) the publication was an full-length original research, (3) at least one group of subjects were healthy combat sports or martial arts' athletes, (4) the study included device dedicated to measure strike force in combat sports, (5) articles were included, even if there was no control group. Studies were excluded if they (1) did not contain human participants, (2) training devices were based on virtual reality technology, (3) the study type was a systematic review, meta-analysis or other non-empirical article.

Measures

Three reviewers (AA, AB and BG) extracted the following information independently from the included studies: (1) characteristics of the participants (including age, body mass and height, sport discipline, sports level and training experience), (2) characteristics of the devices (conceptualization, design and construction), (3) characteristics of the studies. Data were collected and organized in Tables 1, 2 and 3. Due to the heterogeneity of variables, populations, and design the systematic review and meta-analysis of data were not feasible.

RESULTS

Data synthesis

Computerized literature search included five databases and contained a total number of 4028 articles. After title selection and the removal of duplicates, abstracts of 299 original research papers were reviewed for eligibility. Full text of 22 articles was evaluated in detail. Finally, 9 articles met inclusion criteria (Figure 1).

Participants

The total sample size in reviewed articles was 160 participants (111 male, 49 female) from which majority (95) were athletes of different level of performance. The most commonly assessed athletes were boxers and taekwondo athletes, and each group was exclusively selected for five out of ten studies. The detailed characteristic of participants was presented in Table 1.

Concept, construction and design of devices Manikins

The boxing manikins were specially equipped human shaped models used to simulate the human body during a single or a series of punches/kicks. In the study of [16] the boxing manikin was designed to simulate head and upper body of a boxer. The four tri-axial piezoelectric 9366AB force transducers were mounted between front and back frame aluminium frame, where the manikin was permanently mounted. The force signals were passed to amplifier and then to analog-to-digital converter to enable to computer to process dynamometric data. However, in the studies of [14, 10] the boxing manikin had more human-like shape and was dedicated to evaluate kicking performance. The base of manikin was filled with water to maintain its stability. The model was made from heavy dense foam and was equipped with a force platform inside of a torso. The force platform was constructed of two wooden plated of 25 diameter each, which included 5 piezoresistive pressure sensors in pentagonal structure. The height of Smith's manikin was adjustable to the anthropometric features of the trainees, while the Falco's manikin was adjustable to 3 heights of 160, 173 and 188 cm.

Punching bags

In order to evaluate the punching and kicking performance [1] utilized a long cylinder-shaped bag (L = 1.8 m, D = 0.42, mass = 41 kg) with a shock absorbing outer layer, equipped with two 3D

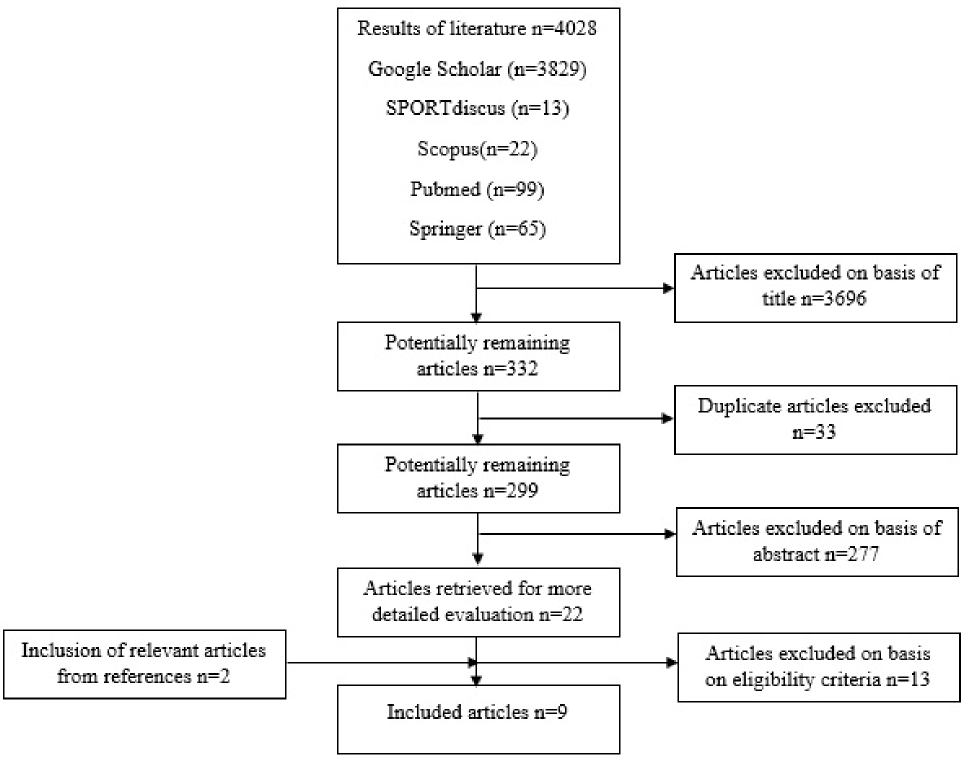


Figure 1. The flowchart for the literature search process.

Strain gauge – is a device used to measure strain on an object. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern.

MMA – mixed martial arts (Piepiora and Witkowski [27] call MMM practitioners neo-gladiators, because this formula of hand-to-hand fighting does not meet the formal criteria of sport within the meaning of the Olympic Charter).

Częstochowa declaration 2015: HMA against MMA – "continuous improvement of health through martial arts as one of the most attractive form of physical activity for a human, accessible during entire life should constantly exist in public space, especially in electronic media, to balance permanent degradation of mental and social health by enhancing the promotion of mixed martial arts – contemporary, bloody gladiatorship, significant tool of education to aggression in a macro scale".

Gdansk 2nd HMA World Congress Resolution – **Article 1** The white flag with five interlocking "Olympic rings" is the most recognizable symbol in the global public space. Neither did the resurrected idea of Olympia, "Citius, Altius, Fortius" save humanity from the horrors of two world wars, nor did the declared mission of the International Olympic Committee (IOC): "1. (...) the promotion of ethics and (...) ensuring that, in sport, the spirit of fair play prevails and violence is banned" (Olympic Charter, p. 18) stop the pathology of permanently educating contemporary man in aggression. **Article 2** Likewise, symbols (a sword pointed downwards surrounded by five rings) and motto ("Friendship through Sport") of Conseil International du Sport Militaire (CISM) did not stop soldiers from killing each other and murdering people after 1948 (the year of establishing CISM, the second largest multi-sport discipline organization after the IOC, and also the year of the Universal Declaration of Human Rights). **Article 3** Although there are five identical combat sports in the Olympic Games and the Military World Games, their potential is still not used to meet the second of the Fundamental Principles of Olympism: "(...) to place sport at the service of the harmonious development of humankind, with a view to promoting a peaceful society concerned with the preservation of human dignity” (Olympic Charter, p. 13). **Article 4** Boxing and wrestling cultivate the traditions of ancient Olympism. Judo and taekwondo have given martial arts humanistic and health attractiveness. Fencing combines this tradition with modernity in the spirit of chivalry. Aiming dynamic offensive and defensive actions directly at the opponent’s body (irrespective of the protectors used) in such a way as not to hurt is a measure of respecting those knightly rules. This rule harmonizes with the principle of respect for the opponent’s as well as one’s own corporeality and dignity over the vain victory at all costs. **Article 5** For the civilized individual and the society for whom human health and dignity are the common good, participation, in any role, in brutal shows of people massacring each other cannot be a standard of the quality of life. Neo gladiatorship camouflaged under the banner of martial arts or combat sports is a slight to the Fundamental Principles of Olympism, but also to the Universal Declaration of Human Rights. Therefore, this Resolution should inspire as many actors of Knowledge Society as possible jointly to oppose any deformations of the mission of Olympism and sport. The expansion of the pathology of unauthorized naming neo gladiators as combat sports athletes will soon turn the Fundamental Principles of Olympism into their own caricature – objective indicators are a testament to the devastation of all dimensions of health by the practice of legal bloody pageants [28].

Table 1. Basic characteristics of the participants in included studies.

Source	Combat sport (martial arts)	Sex		Age [years]	Weight [kg]	Height [m]	Level of competition	Experience [years]
		M	F					
Smith M et al. (2000) [16]	boxing	7	0	23.1 ±1.2	69.9 ±8.6	1.78 ±0.06	elite	11.5 ±1.4
		8	0	23.5 ±3.3	73.4 ±8.2	1.75 ±0.05	intermediate	5.7 ±1.3
		8	0	23.6 ±3.2	78.5 ±8.9	1.79 ±0.02	novice	1.5 ±0.2
Pierce J et al. (2006) [8]	boxing	12	0	27 ±9	78.95 ±19.95	-	legendary blue horizon	-
Falco C et al. (2009) [14]	taekwondo	15	0	21.57 ±4.75	-	-	expert	at least 4
		16	0				novice	
Estevan I et al. (2011) [10]	taekwondo	13	0	26.56 ±2.23	72.04 ±12.67	1.77 ±0.86	medallists	at least 4
		14	0				non medallists	
Buśko L et al. (2016) [1]	boxing	13	7	17.0 ±1.1	68.9 ±12.4	1.7 ±0.1	-	3.1 ±1.6
	taekwondo	14	14	18.7 ±3.1	62.9 ±8.1	1.75 ±0.13	-	8.1 ±2.8
Šiška L et al. (2016) [20]	boxing	4	8	20.6 ±4.4	67.6 ±10	1.708 ±0.084	Boxing club Ruzinov 821	2.6 ±1.6
Ramakrishnan K et al. (2017) [21]	kung fu	2	0	31.6 ±10.3	86.2 ±20.5	-	Australian Defence Force Academy	-
	karate	6	2					
	taekwondo	3	0					
	Muay Thai	3	0					
	MMA*	1	0					
	judo	1	0					
	untrained	26	8	28.1 ±7.2	77.4 ±17.4	-	-	-
Buśko K and Nikolaidis P.T. (2018) [15]	taekwondo	6	0	17.7 ±0.7	62.3 ±6.0	1.795 ±0.041	World Taekwondo Federation	6.5 ±1.6
Jovanovski A and Stappenbel A (2020) [5]	boxing	21	10	-	72.7 ±11.7	1.74 ±0.07	novice	-

* MMA (see glossary)

accelerometers located on the edge surface of the punching bag's inner cylinder base. The dedicated software enabled the calculation of strike forces in three directions based on the mass of the punching bag and the sum of acceleration of upper and lower edge of the punching bag. The calculation of the point in which the strike was delivered was calculated taking into account moments of inertia against the punching bag's centre of mass, upper and lower edge acceleration, distance between these two points and the force of strike. The accelerometer-based approach has been also used by [20]. The subjects were asked to deliver a punch into the FiTRO agility plate mounted on athletes' eye level. The single accelerometer was placed on the opposite side of the punching bag (L = 1.9 m, mass = 50kg) approximately at the height of the centre of the plate. The calculation of the punch force was based on the mathematical formula, where force is a product of punching bag's mass and acceleration.

In contrast, in the study of [15] relatively small (L = 0.5 m, D = 0.48 m) punching bag suspended on a set of stabilizing ropes with in-built strain gauge was used. The system was appropriate to measure the resultant reaction force in the plane perpendicular to the cylindrical surface of the punching bag. The punching bag was externally connected with the strain gauge amplifier equipped with the analogue-to-digital converter.

All of the punching bags were equipped with diodes which played a role of visual signal to start the punch [20] or were guiding the strike sequences [1, 15].

In-glove systems

The in-glove systems were introduced in the studies of [8, 5]. The systems enabled evaluation of the boxers technique and punching physics during matches within the boxing ring. It also addressed the problem of overestimating the actual force delivered by boxer while punching an inanimate object in comparison to punching the moving opponent. The systems took into account the multidirectional components of punch, as well as dynamic and repeated nature of boxing. In the study of [5] the non-embedded in-glove sensors consisting of 3D accelerometers and piezoresistive force sensors were used. The sensors were 1-ich and covered the impact area on the fist. Similarly, in the study of [8] the lightweight, flexible force sensors were adjusted to the hitting area (120 cm^2), however were located inside of the foam padding of the gloves. In this study the authors used capacitive force sensors which were originally designed and patented for isometric knee muscle torque measurements [22]. Both systems were designed to obtain maximal force of impact and caused no discomfort to the athletes during punching assessment.

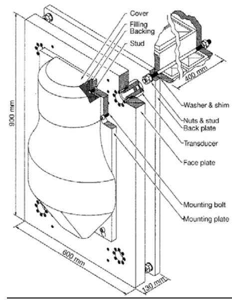
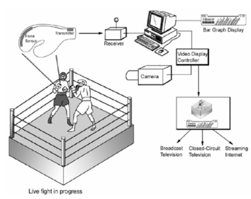
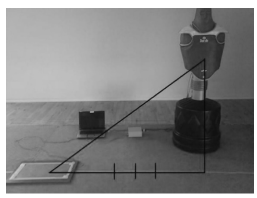
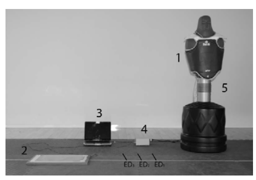
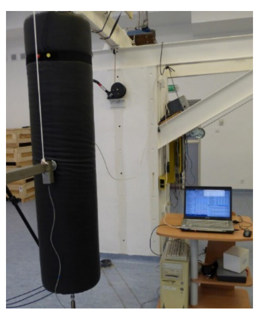
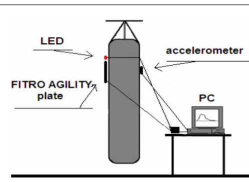
Other devices

In the study of [21] the 'Kick test rig' was designed to measure kick force and displacement of the target (Table 2). The target was composed of the vertical plate of a contact area of 400 mm x 275 mm made from aluminium, industrial strength vinyl and padded with high-density foam in order to prevent injuries. The target was fixed on steel beam which served as a carriage moving in horizontal axis. The force was measured by a S-type Dacell load cell with a capacity of 1000 N, while the displacement of the target was obtained by a linear variable displacement transducer attached to the target.

Calibration

Most likely, the calibration of punching bags and force plates involved the pendulum-like unit of a known weight which was striking against measurement device. In the study of [16] the pendulum impactor was a steel ball in the shape of a fist covered by a boxing glove (Top Ten, Germany) which hit the dynamometer manikin at an angle of 90° with a mass of 4.4, 20, 45 and 60 kg. Four impacts at each calibration mass were filmed what allowed a comparison between recorded and calculated impact forces. The force measurement error was less than 3%. In the study of [1], the dynamometric impact hammer equipped with a strain gauge-based force transducer was suspended and pulled back away from punching bag in order to deliver 5 to 8 strikes to punching bag. The transducer was connected to light metal spherical cap through which strike force was transferred onto the dynamometric punching bag. The values of impact forces obtained by strain gauge were compared to the values of force obtained and calculated from accelerometers embedded to the punching bag. The measurement error of force was less than 1%. In the study of [21] the 'kick test rig' was calibrated using 40 kg steel cylinder suspended on a steel cable. The measured energy was compared with the energy applied to the platform during impact showing that 98% of energy from the pendulum was transferred. These results implied, that only small amount of energy was lost in friction and inertia.

Table 2. Technical characteristics of devices dedicated to measure force of striking in included studies.

Source	Combat sport (martial arts)	Construction of training simulator				Additional devices used in the study
		Type	Device design	Schematic representation/ Photograph	Software	
Smith M et al. (2000) [16]	boxing	Boxing dynamometer	Four triaxial piezoelectric 9366AB force transducers (Kistler, Alton, UK), boxing manikin designed to simulate the head and upper body of the oxer, 9851 charge amplifier system (Kistler, Alton, UK), 12-bit PC26AT analog-to-digital converter		Provec 5 clinical data software	A 16-mm Photosonics 500 cine film camera (Thame, UK), fitted with a Sigma 0.024-m lens (Whitbys, Chichester, UK), NAC DF-16C projector (International IML, Thame, UK), Terminal Display System TP1067 digitizing tablet (Bracknell, UK)
Pierce J et al. (2006) [8]	boxing	Best Shot System ™ by Sensorpad Systems, Inc. (SPS; Norristown)	Boxing gloves (modified Everlast 1008 8-ounce and 1010 10-ounce Pro-Fight) incorporating the best shot System (lightweight, flexible force sensor embedded in the scoring section of the glove), remote receiver, PC		-	-
Falco C et al. (2009) [14]	taekwondo	A201 moby FLEXIFORCE Company	Freestanding boxing mannequin, a force platform, made with two circular wooden plates of 25cm diameter, five piezoresistant pressure sensors in a pentagonal structure on the mannequin		Visual Basic 6.0	HP computer, microcontroller
Estevan I et al. (2011) [10]	taekwondo	A201 moby FLEXIFORCE Company	Freestanding boxing mannequin, a force platform, made with two circular wooden plates of 25cm diameter, five piezoresistant pressure sensors in a pentagonal structure on the mannequin		Visual Basic 6.0	HP computer, microcontroller
Buśko L et al. (2016) [1]	boxing taekwondo	Boxing Training Simulator (BTS-4AP-2K)	Dynamometric punching bag (1.8 length, 0.42 diameter, 41 kg mass, stiff core, shock absorbing outer layer) with an embedded two tri-axial accelerometers mounted on the edge surfaces of the punching bag's inner cylinder base		BTS6v0 software	Special dynamometric impact hammer equipped with a strain gauge-based force transducer equipped with a light metal spherical cap
Šiška L et al. (2016) [20]	boxing	BOX-CHECK	the punching bag with attached accelerometer, FITRO agility plate, light emitting diode which present visual stimuli (red lamp) connected to the PC with dedicated software		-	-

Source	Combat sport (martial arts)	Construction of training simulator				Additional devices used in the study
		Type	Device design	Schematic representation/ Photograph	Software	
Ramakrishnan K et al.(2017) [21]	martial arts	Kick Test Rig	Vertical plate with a contact area of 400 x 275 mm, rectangular hollow section steel beam, twin-airbag system, S-type Dacell load cell, linear variable displacement transducer		-	Casio Ex-F1 camera
Buśko K. and Nikolaidis PT (2018) [15]	taekwondo	Boxing Training Simulator (BTS-3)	Dynamometric punching bag (0.5 m length, 0.48 m diameter) with an embedded strain gauge, 2 signal diodes on an upper section of the bag, strain gauge amplifier, signal conditioning sub-assemblies, analog converter; connected with PC by USB interface; hanged on stabilization rope		BTS5v0 specialist software („JBA" Zb. Staniak, Poland)	(1) Kistler force plate Type 9281A (2) special torque meter type SMS1 and SMS2 (3) Monark 874 E cycle ergometer
Jovanovski A and Stappenbelt A (2020) [5]	boxing	Embedded in-glove measurement system	In glove sensors: tri-axial accelerometer and piezo-resistive force sensor	-	The Bluehill Software	static measurement system

Different approach has been used to calibrate force sensors located in the boxing glove or boxing manikin. In the study of [5] the piezo-resistive force sensors were calibrated by punching a static measurement system utilizing simple load cells for force and laser displacement for glove speed measurements. The static measurement system generated a calibration coefficient applied to the voltage output of the force sensor in order to provide the value of force in N. Similarly, in the study of [14] calibration allowed to relate the voltage output (obtained in the tensor amplifier) to the force acting on the sensor (expressed in N). It was realized by linear interpolation and placing 2 kg by 2 kg until reaching 20 kg, and 10 kg by 10 kg until reaching 110 kg in total.

At last, in [8], the drop platform apparatus was repeatedly lifted and dropped on the boxing glove from various heights. These created impacts of known forces measured by the load cell attached to the centre of the platform. The average error of force was 4%.

Measuring outcomes

The values of the impact forces associated with striking depend on several factors, such as the limb involved (lead or rear), type of the task, gender, experience, athlete's body weight and environment in which the assessment has been done (Table 3).

The influence of task: punching

The type of the punch did not show significant differences in the impact forces in elite taekwondo practitioners (straight punch 1659 N ± 254.2 vs. hook punch 1843.8 N ± 453.3) [15]. The rear hand punching reached higher values of impact forces than lead hand in elite male boxers: 1592.5 N ±507.1 vs. 1102.9 N ±430.7 [1], 4800 N vs. 2847 N [16], female elite boxers: 1170.7 N ±165.3 vs. 848.4 N ±218.5 [1], intermediate boxers: 3722 vs. 2283 N, and novice boxers: 2381 vs. 1604 N [16]. Higher impact forces generated with rear limb were associated with significantly higher maximal joint torques in flexors and extensors of elbow joint in the same limb (54.2 Nm ±8.5 vs 61.7 Nm ±12.7) [15]. Additionally,

Table 3. Summary of included studies.

Source	Aim	Task	Limbs involved	Procedure	Analysed variables	Conclusion
Smith M et al. (2000) [16]	Development of a tri-axial boxing dynamometer capable of discrimination between different punch deliveries.	Punching (straight punch)	Both	Straight punches to the head with max effort during simulated competitive boxing bouts, either singly or in 2 or 3 straight punch combinations, in a prescribed sequence from an audio cue.	maximal force [N]	The boxing dynamometer discriminated effectively between punching performance at 3 standards of performance and between the punching force of the rear and lead hands.
Pierce J et al. (2006) [8]	To assess the punch forces during professional boxing matches	Punching (various types)	Both	The matches held in the boxing ring in front of a crowd for each fight. Each fight was professionally refereed and judged. Totally 6 boxing matches.	punching force [N]	The system is able to measure punch force during boxing match. It brings benefits for training (punch effectiveness), judging (objective measure of punch), and monitoring boxers (safety benefits).
Falco C et al. (2009) [14]	To examine the impact force and to explore whether the execution distance affects kicking impact force and execution time.	Kicking (bandal chagui, roundhouse kick)	One	2 trials of 3 distances, recorded considering the subjects' leg length (medium distance) and, respectively, 1/3 up the leg (large distance) and 1/3 down the leg (short distance).	impact force [N] execution time [s]	Expert were more powerful in longer distances and faster than novice in all distances. Distance did not have an influence on impact force as competition level increases.
Estevan I et al. (2011) [10]	Compare the max impact force, execution time, and impact time in the kicking to the head in relation to the execution distance and weight according to the athletes' competition level	Kicking (roundhouse kick)	One	Kick "as strong and fast as you can when you are ready" in medium, long, short distances. 25–30 seconds of rest between kicks; 2 min between distances. 2 kicks for each distances.	Impact force [N], Execution time [s], impact time [s]	No differences were observed in impact time in any of the execution distances between groups. Medallists were hitting with less execution time and greater max impact force than non-medallists.
Buśko L et al. (2016) [1]	To design a new device measuring punching and kicking forces that could replace the strain gauge- based measurement system used formerly.	Punching (straight, hook)	Both	3 single punches (both techniques) with the rear hand and lead hand to develop max punching force.	maximum force [N], reaction time [s]	The system is sufficiently functional to be used for diagnostics in taekwondo while at the same time offering greater diagnostic capabilities for boxing.
		Kicking (apdolio, dwit chagi)	Both	3 kicks (both techniques) with the lead leg and rear leg to develop maximal kick force.		
Šiška L et al. (2016) [20]	To assess the reliability parameters of a „Box-check" device	Punching (direct punch)	Lead hand	On the visual signal the punch execution with step towards the boxing bag. 2 series with 10 punches (30 s break between) and 2 series with 10 punches (10 min break between)	duration of a punch [ms], force of a punch [N], ICC	Device „Box-check" may be used during whole training session i.e. 50-100 punches for different combination of front, rear and hook punches
Ramakrishnan K et al. (2017) [21]	To design and construct a kick test to measure the force and displacement of a vertical target subjected to kicking and calculate total energy of the kick.	Kicking (front kick)	-	At least 3 trials of kick with maximal energy.	force [kN], energy [J]	The kick energy was increasing with body weight of participant and gender, however was not with martial arts training. 1 in 100 adults will be able to kick with energies exceeding 215 J.
Buśko K and Nikolaidis PT (2018) [15]	To examine biomechanical characteristics of taekwondo athletes comparing their kicks and punches with laboratory tests of muscle strength and power.	(1) Punching (straight, hook) (2) Kicking (apdolio, dwit chagi)	(1) rear hand (2) both legs	Jump on the force plate CMJ and SPJ, muscle strength, force of punches and kicks, F-v relationship. 3 trials of straight punch, 3 trials of hook punch, 3 apdolio kikcs and side apdolio kicks with both legs during 120 s simulation of a fight. And dwit chagi kicks with the rear leg also during 120 s simulation of a fight.	power [W], height [m]. peak joint torque [Nm]; max force [N]; force-velocity and power-velocity relationship [vpm], punching bag reaction force [N]	The results are likely to show that the punching and kicking force may depend on other factors, e.g. technique.
Jovanovski A and Stappenbelt A (2020) [5]	To investigate non-embedded in-glove measurement device.	Punching	Dominant (rear) hand	Single punches during 1 min using the dominant hand against the static measurement system with the dynamic measurement system.	force [N], voltage [V], acceleration [g], velocity [m/s], power [W]	Punching parameters correspond well with prior studies using alternate measurement approaches. The calibration of system yielded a correlation coefficient of 0.85.

in straight punching the reaction time of female boxers were significantly longer while delivering the punch with rear hand in comparison to lead hand (0.619 ±0.025 s vs. 0.512 ±0.066) [1].

The influence of task: kicking

In kicking, five types of techniques were assessed: front kick, *apdolio*, *dwit chagi*, *yop chagi* and *bandal chagui* while the technique of front kick and *bandal chagui* were not described in the text. *Apdolio* was a roundhouse kick, which is used to attack, defend or counter-attack the opponent. The *dwit chagi* was a back kick in which the athlete turns the body away front the target and pushes the back leg straight toward the target, hitting it with a heel while watching over the shoulder. And finally the *yop chagi* was a side kick during which the athlete rises knee of kicking level, straighten toward the target throughout sagittal plane so that the heel and the outside of foot strikes the target.

The mean force in front kick varied from 1170 N to 7790 N and the front kick energy from 34 J to 178 J with the 67% of the participant of mean energy above 100 J. No comparison between left and right leg was presented [21].

According to [1, 15] the force of the *apdolio* kick delivered with rear leg was significantly greater than the kick delivered by lead leg (1206.7 N ±239.5 vs. 2072.3 N ±472.2 and 965.3 N ±234.1 vs. 1511.6 N ±271 [1], 3541.3 N ±113.3 vs. 3205.3 N ±965 [15]). The high impact forces of rear leg were associated with high joint torques of hip flexors and extensors. In addition, strong relationship between force and power in spike jump was observed for lead and rear leg in *apdolio* kick [15].

No significant differences in force (female: lead 2461.1 N ±494.7 vs rear 2490.3 N ±846.2 and male: lead 3514.6 N ±1190.4 vs rear 3426.1 N ±911) and reaction time (female: lead 0.671 s ± 0.166 vs rear 0.716 s ±0.075 and male: lead 0.694 s ±0.078 vs rear 0.693 s ±0.080) were found between lead and rear leg for *dwit chagi* kick [1]. According to [15] the force delivered by the rear leg during *dwit chagi* (3568 N ±1306) was slightly higher than the one delivered by *apdolio* (3541 N ±1130.3).

The differences between right and left lower limb has been found in peak force delivered during *yop chagi* (right: 9015 N ±2382, left 8294 N ±2308), mean force (right 4426 N ±2110, left 4454 N ±2293) and stroke impulse (right 38 Ns ±13, left 42 Ns ±15).

The influence of expertise

Generally, the force of punch was increasing with the level of expertise. The highest maximum punch forces recorded in the included studies were 6900 N [20] in male boxer who completed at least 3 competitive boxing matches, 5771 N [16] and 5358 N [8] in elite boxers. The lowest maximum punch forces were recorded in novice and were equal to 3845 N [5]. The mean peaks punching force were significantly greater in elite than intermediate, and intermediate than novice (rear hand: 4800 N >3722 N >2381 N, lead hand: 2847 N >2283 N >1604 N) [16]. In roundhouse and *bandal chagui* kicking, expert taekwondo athletes had higher mean impact forces (1994.03 N ±537.37) than novice (1477.90 N ±679.23) [14]. The elite taekwondo athletes were also better than novice when the distance from the target was extremely short (elite 1829 N ±161 vs novice 1329 N ±167) or long (elite 1760 N ±149 vs novice 1203 N ±154). In addition, the significant difference in peak forces delivered by front kick was found between trained in martial arts (5200 N) and untrained participants (3200 N) [21].

In contrast, according to [8], boxing experience, measured by the number of professional bouts and the boxing success (measured by the percentage of previously won bouts) were not a significant predictor of a punch force during boxing match. In martial arts no difference was found between untrained and trained in energy delivered during a front kick, even when it was normalized to the body weight [21]. No difference in kicking force was found between medallists and non medallists when the distance from the target was average [10].

The influence of body weight

The significant correlation between participant's weight and front kick energy and mean front kick force was found, however this relationship was not linear [21]. Interestingly, in the study of [14, 10] the significant correlation between weight and kicking force was found in novice taekwondo athletes (non medallists), however was not found in elite (medallists). According to the same authors, the elite athletes generate greater impact forces due to the use of principle of kinetic chain, while the non-elite compensate technique deficiencies with the use of their bodyweight. However, the study of [16] showed that the greater mass of novice boxers did not lead to higher punch forces obtained by novice when compared to elite athletes. These results indicated that using of body weight in novice was not a enough to compensate the effect of poor technique on final impact forces. No influence of body weight on punching forces was also shown in the study of [8]. The mean impact forces delivered across different weight categories were not significantly correlated with elite boxers' body mass [8]. The highest mean punch forces were observed in Light Middleweight (1149.2 N) and Light Welterweight (1124.3 N), while the lowest in Super Middleweight (866.6 N) and Cruiserweight (920.5 N). Similarly, the cumulative punches force which is the function of punch force, number of punches delivered and the number of rounds showed no relationship with boxers' weight [8].

The influence of gender

Four of ten included studies involved female and male participants, however in two of them the comparison between genders was not presented [20, 5]. The intergender differences have been found among boxers and taekwondo practitioners. In boxers, the differences between male and female where observed in force (female 1170.7 N ±165.3, male 1592.5 N ±507.1) and reaction time (female 0.619 s ±0.025, male 0.528 s ±0.068) of straight punch delivered by rear hand. In taekwondo, the higher impact forces and shorter reaction time were observed in male subjects when *apdolio* kick was delivered with the rear leg (impact forces: female 1511.6 N ±271, male 2072.3 N ±472.2, reaction time: female 0.682 s ±0.058, male 0.631 s ±0.066) and lead leg (impact forces: female 965.3 N: male 1206.7 N, reaction time: female 0.718 s ±0.084, male 0.644 s ±0.064) [1]. Similarly, the force of *dwit chagi* kick delivered by rear (force: female 2490.3 N ±846.2, male 3426.1 N ±911) and lead leg (force: female 2461.1 N ±494.7, male 3514.6 N ±1190.4) distinguished male and female participants [1]. According to [21] gender had strong influence on the kick energy, even if it was normalized to the body weight of the subject.

The influence of experimental conditions

The results of punch force during boxing matches were not straightforward. According to [8], the average values of punch force during matches varied from 920.5 N ±508.5 in cruiserweight to 1149.2 N ±665.8 in light welterweight (the other weight categories: junior lightweight, super middleweight, heavyweight with values in between). These results indicated lower values of punch forces obtained during boxing matches than while delivering a punch to inanimate object. Similar results were observed in the kicking performance, where the peak forces were greater for the test of an individual kick than in a 120 s simulated fight [15]. In contrast, in the study of [5] the average punch force in novice boxers were twice higher than in the study of Pierce et al. [8] and were equal to 2310 N ±3280. These values were greater than when the athletes were instructed to deliver a single punch to boxing bag or impact plates [1, 15].

DISCUSSION

The presented study reviewed recent information regarding the usefulness of sport-specific devices dedicated to measure striking force in combat sports (martial arts) athletes. Overall, the most of the included studies showed the significant influence of gender, level of expertise and the striking technique on the impact forces associated with punching and kicking. However, these results must be interpreted with caution due to the large diversity of measurement systems, used sensors and the environment in which assessment has been done.

In the majority of included studies, the striking performance was assessed in non-ecological conditions. It means, that the punch/kick was performed in decontextualized situation and was not related to the sport practiced [23]. Isolated striking to non-moving object were assessed by the target-based measurement devices, such as punching bags, boxing manikins or impact plates. This restriction is not trivial, since some studies have shown, that the punch forces observed in ecological conditions (e.g. during boxing match) were lower when compared to the ones observed in non-ecological context [8, 15]. Previous authors [8] highlighted that in the ring, the target is a living object, who can avoid a punch completely, partially evade it to reduce the force of impact, or receive the punch before optimum reach. Thus, the dynamics of the ring reflect a considerably different task than that of a laboratory simulation. The assessment of the impact forces in sport-specific conditions opens up new possibilities in analysing and refereeing combat sport performance. For example, it could objectify the referee decisions and assign points depending on the punch impact force delivered by an athlete during match [8, 11].

In most of the studies included, the punch or kick was delivered to an object which is not comparable in mass and biofidelity to the human body [24, 25]. What is more, many of the strike measuring devices have resulted in values that do not fully reproduce the attacking force and multidirectional components of a strike, nor do they consider the dynamic repeated nature of combat sport. Generally, it is difficult to find consistencies in research on the impact force of various punches or kicks. As highlighted by previous authors, there are several possible reasons for it [18, 14, 15]. First is the variation in the striking technique. Another issue is the type of padding material used in boxing gloves or target-based measurement device. On the one hand, the highest impact forces would be obtained while deliver a strike to non-padded, rigid object. For example a kick on a concrete wall would produce greater impact force in comparison to a kick delivered to a soft foam [21]. On the other hand, delivering a maximum strike to a stiff object could result in increased risk of injury. Third reason might be the size of the target which also varied between studies. According to Fitts' law, the size of the target determine the movement velocity and consequently may influence the striking force [26]. Thus the size, elasticity or inertia of the target have a strong impact on the evaluation of the impact force [24, 18, 14].

Moreover, the measurement equipment used to register the data, as well as the mathematical model implemented to calculate eligible variables, has a direct influence on the final value of impact force. Therefore the data obtained from different types of force sensors (strain gauge, piezoelectric sensors, S-type Dacell load cell) should be compared with cautions with the force values calculated on the basis of accelerometer data. However, in [1], verification of method accuracy revealed that the measurement force error in accelerometer-based approach was less than 1%.

At last, reviewed articles showed that several papers did not include proper statistical description (e.g. did not report effect sizes) and none of the studies included sample size justification. Comparisons were based on small sample sizes, what in turn could infer statistical results and influence author's conclusions.

CONCLUSIONS

Current review revealed that there are plenty of valid, accurate and reliable devices which opens up new possibilities in enhancing combat sport training and performance. Unfortunately, because of the large methodological and technological diversity, the results obtained by previous authors cannot be directly compared. That is why, the future research perspectives should include the evaluation of diverse groups of athletes across different force measurement devices. This approach would allow for estimation of the measurement differences resulting from the device construction.

HIGHLIGHTS

- The devices dedicated to measure the force of strike were equipped with in-built set of piezoresistive sensors or strain gauges.

- Assessment of striking forces based on acceleration data shows the measurement error less than 1% in comparison to strain gauge measurements.

- The elite athletes generate greater impact forces in kicking due to the use of principle of kinetic chain, while the non-elite compensate technique deficiencies with the use of their bodyweight.

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