Sports Engineering (2022) 25:5
https://doi.org/10.1007/s12283-022-00368-3

TECHNICAL NOTE

Validity and reliability of impact forces from a commercially instrumented water-filled punching bag

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Accepted: 24 February 2022 / Published online: 25 March 2022

Abstract

Measuring striking forces is important to provide actionable insight for training and performance enhancement for combat sport athletes. Recent technology may provide a low-cost solution to an otherwise complicated kinetic assessment. The aim was to assess the reliability and validity of a water-filled training bag and integrated sensor for measuring peak impact force. A pendulum design was used to swing a range of known mass loads (kettlebells) from various heights to impact a stationary 21″ Aqua Training Bag®. For each condition, the momentum of the mass at impact was calculated and compared with the measured impact force from a pressure sensor affixed to the side of the water-filled bag. Peak impact force was strongly associated with calculated momentum ($r(18) = 0.96$ [0.91, 0.99], $p < 0.001$), with a high degree of shared variance (92.7%, $F(1,18) = 229.9$, $p < 0.001$). There was almost perfect agreement for all reliability loading conditions (ICC = 0.995–0.999) and typical error was ≤ 5% (CV = 3.3–5.1). Impact kinetics from the sensor appear to be reliable and valid and may be integrated into practice and research. However, the utility of the instrumented bag for striking kinetics of athletes, and thus practical utility when used in the field, requires further investigation.

Keywords Boxing · Aqua · Combat · Sensor · Pressure · Water bag

1 Introduction

Impact kinetics are a fundamental component of many combat sports (e.g., boxing). Consequently, measuring the mechanics underlying striking can give insight into the status of an athlete, and aid in characterizing the transfer of training to an applied performance metric [1, 2]. Numerous measurement devices exist in the research [3], which are typically high-cost technologies that are impractical outside of the clinical environment [4]. Although alternatives exist [5], such devices have seen limited uptake outside of research environments. Recently, a 'smart bag' which integrates a pressure sensor into a water-filled teardrop bag has reached the market and purportedly provides real-time kinetic assessment of peak impact forces by detecting pressure changes in the fluid medium [6]. While seemingly gaining popularity in the public space, the validity and reliability of this device for measuring impacts are unknown. Should data from this sensor be accurate, its low-cost and practical nature could feasibly improve the accessibility and therefore understanding of striking kinetics for the wider public and research community. This research aimed to quantify the reliability and validity of the Aqua Training Bag® sensor (Model: Sensor, Aqua Training Bag, New York, US) for measuring peak impact force.

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2 Methods

2.1 Experimental approach to the problem

This was a descriptive study to determine the validity and reliability of peak force measurements from impacts on a water-filled training bag and integrated sensor. A laboratory

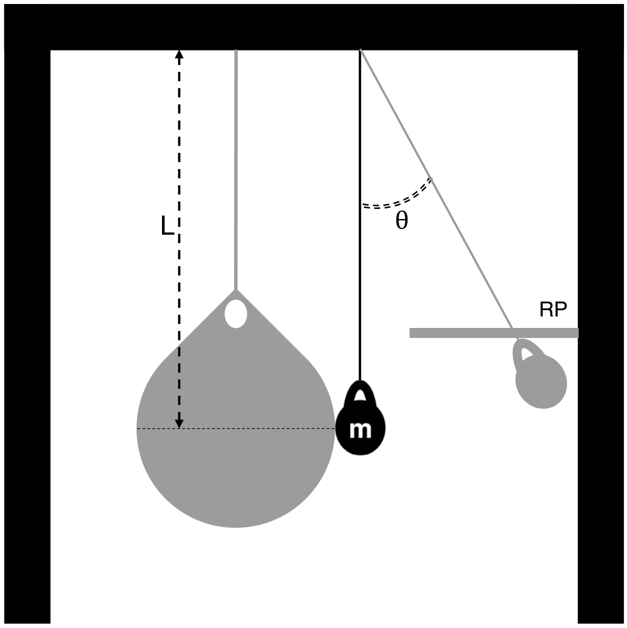

Fig. 1 Pendulum design with the instrumented punching bag suspended where the largest diameter of the bag (contact point) was one meter below (*L*) the fixed attachment point. The kettlebell (mass, *m*) was lifted to the release point (RP) manually before being released to where it strikes the bag. The kettlebell and instrumented punching bag were suspended so that when hanging still, they minorly contacted

setup consisting of a simple pendulum design was used to swing a spectrum of known mass loads and impact momentum, across a range of measured travel arcs, to contact the bag in a controlled fashion and simulate human punches. The data from this study should help inform practitioners and researchers on the utility of this device for training and performance monitoring purposes, and potentially inform athletes, coaches, and scientists in a more robust and exact manner.

2.2 Procedures

A commercial water-filled teardrop punching bag (~86 kg, 0.53 m diameter; Model: 190 lb, Aqua Training Bag, New York, US) and integrated sensor were used to provide a measurement of impact kinetics across a known range of momentum (ρ) values. The sensor was inserted and affixed into the side of the bag, as instructed by the manufacturer, and provided impact-by-impact readings of peak force (F_{peak}) by detecting intra-bag changes in fluid pressure. Peak force data were sent via Bluetooth to the manufacturer-provided cell phone application (AquaTrainingBag, NCi Technology Inc., Version 1.1.1).

Known mass loads (provided via kettlebells) were swung into the bag using a pendulum design (see Fig. 1). The loading and setup characteristics were selected to provide a range of standardizable striking force measures, simulating a human punch. The setup allowed the arc of travel (θ) to be accurately measured across different mass loads and standardized across trials of the same mass by ensuring a consistent release point (RP, Fig. 1). The length of the pendulum was standardized across loads (1 m), to ensure consistent contact with the point of the greatest horizontal diameter of the bag. For each trial, the appropriate load was attached to the pendulum via an inelastic tether, manually lifted to the set height against a fixed bar (per the given θ), and released by the operator without undue influence (e.g., they did not push the load) to swing and contact the bag. Any trials during which operator influence was evident (e.g., the kettlebell spinning before contact) were removed from the dataset and repeated. For all trials, mass, θ, and F_{peak} were manually recorded for computational and statistical analysis.

2.2.1 Validity

Six loads ranging in mass (4–24 kg) were released across known θ conditions (30°–67° in ~ 10° increments). A total of 10 trials were conducted at each loading and θ combination. All trials were conducted in the same session, by a single operator. Testing condition characteristics and F_{peak} data were recorded for analysis, with the latter being used to determine our criterion measurement. Velocity of the load at impact (v_{imp}) was calculated using energy conservation theorem:

$$v_{imp} = \sqrt{2gL(1 - \cos\theta)} \quad (1)$$

where g is equal to gravity (9.81 m.s.s^{-1}), and L the length of the pendulum holding the swinging mass (i.e., 1 m). from point of rotation to the point of contact with the bag. Then, ρ at the point of impact was calculated as:

$$\rho = mv_{imp} \quad (2)$$

where m represents the mass of the given loading condition. Friction and air resistance were considered negligible and unaccounted for.

2.2.2 Reliability

Two loads (8 and 16 kg) were attached to the pendulum and each released across two θ conditions (High, 60° and Low, 38° or 41°). A total of 30 trials were conducted for each of the four combinations of load and θ. All trials were conducted in the same session, by a single operator. The F_{peak} data provided by the pressure sensor were manually recorded for analysis against the testing condition.

2.3 Statistical analyses

Following manual transcription, data were imported in raw form into R (Version: 1.4.869, RStudio, R Foundation for Statistical Computing, Vienna, Austria) for statistical analysis. For both analyses, data were visually assessed using the boxplot method (Q3 ± 3 × IQR), and 12 clear outlier trials were removed (presumably due to measurement error of the mobile application). Means and standard deviations of all remaining trials were calculated for each load and θ combination for their respective statistical analysis. Bivariate normality of the validity dataset was confirmed (Shapiro–Wilk, $p > 0.05$) and concurrent validity was assessed using a Pearson's product-moment correlation (r) to provide the association between calculated ρ and measured F_{peak}. A linear relationship between ρ and F_{peak} was visually observed using a scatterplot and normality of the residuals was confirmed (Shapiro–Wilk, $W = 0.939$, $p > 0.05$). Linear regression was used to evaluate the relationship between ρ and F_{peak}. The r and R^2 values were reported to represent the association and shared variance, respectively. Where possible, 95% confidence intervals were calculated and reported. Agreement of $r > 0.8$ was interpreted as very strong [7]. Intraclass correlation (ICC) was used to test the consistency of F_{peak} across various reliability combinations, and coefficient of variation (CV) to test the typical error. Group averages and standard deviations were calculated and reported for each reliability combination. Values of ICC > 0.9 and CV < 5% were interpreted as high variable reliability [8]. The alpha value for all tests was at 0.05.

3 Results

The means and standard deviations for the impact forces across loading conditions are in Table 1. Peak force output detected by the pressure sensor was very strongly associated with calculated momentum ($r(18) = 0.96$ [0.91, 0.99], $p < 0.001$), with a high degree of shared variance (92.7%; $F(1,18) = 229.9$, $p < 0.001$) (Fig. 2).

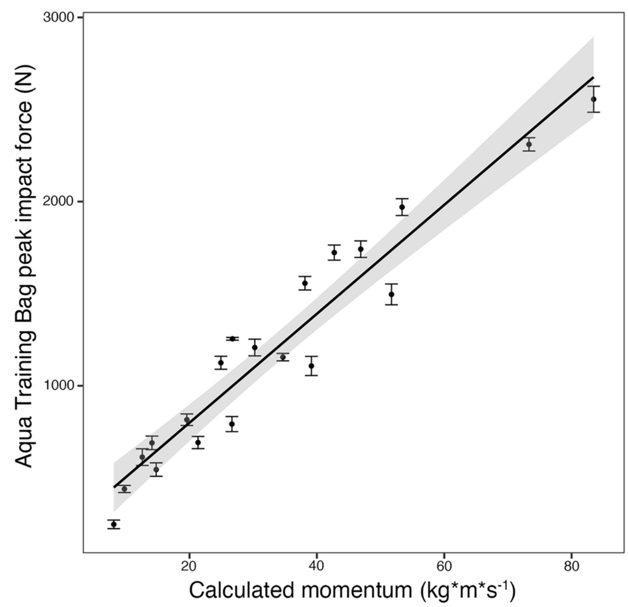

Fig. 2 Validity data collected using the custom-designed pendulum, with 95% confidence level intervals for predictions from the linear regression model. Momentum of the swinging mass at impact and peak impact force measured from the pressure sensor are presented on the *y*- and *x*-axis, respectively. Scatter-plot and error bars represent mean ± standard deviation for each loading condition, respectively

Table 1 Reliability summary statistics of each loading condition

Loading condition	mean ± sd (*N*)	se ± CI (*N*)	CV (%)	ICC (lower CL, upper CL)
Low (θ = 38) + 8.28 kg (*n* = 28)	743 ± 34	6.44 ± 13.2	4.58	0.995 (0.989, 0.998)
Low (θ = 41) + 15.44 kg (*n* = 26)	1150 ± 58	11.4 ± 23.5	5.06	0.995 (0.988, 0.998)
High (θ = 60) + 8.28 kg (*n* = 29)	1197 ± 31	5.71 ± 11.7	2.57	0.999 (0.997, 0.999)
High (θ = 60) + 15.44 kg (*n* = 30)	1886 ± 62	11.3 ± 23.0	3.27	0.998 (0.995, 0.999)

θ release angle of mass, *n* number of trials, *N* impact force in Newtons, *sd* standard deviation, *se* systematic error, *CI 95%* confidence interval, *ICC* intraclass correlation coefficient, *CL 95%* confidence limits, *CV* coefficient of variation in percentage

Low systematic error (< 12 N) and high absolute and relative consistency (CV < 5.1%, and ICC > 0.99, respectively) was observed across all loading conditions (Table 1).

4 Discussion

Using a custom-designed pendulum, the instrumented punching bag appears to provide a reliable and valid measurement of within-session peak impact force. Specifically, absolute consistency (CV) was ≤ 5% for all loading conditions and concurrent validity of impact force was excellent when compared to calculated momentum. As such, the 'smart' water-filled bag instrumented with a pressure sensor appears to offer a reliable, valid, and practical solution to measure, map and monitor changes in impact forces.

Impact data measured by the sensor were very strongly associated with that calculated using the principle of conservation of momentum. In this manner, only a small proportion of variance remained unexplained between the measurements (~ 8%), which is promising when applied to practical settings in similar standardized conditions. Similarly, the data provided by the sensor were highly repeatable, albeit skewed toward greater reliability at higher impact velocities (2.6–3.3% vs. 4.6–5.1%, for high and low velocity conditions, respectively). This might be partially explained by a degree of consistent measurement noise remaining consistent across varying testing conditions, which would be proportionately smaller at high velocity values. Our results are comparable to those reported by Lenetsky, et al. [5], who performed a pendulum validation and reliability test for an accelerometer-equipped bag and inertial modelled kinetics (validity, $R^2 = 0.96$; reliability, CV < 2.5%). One clear benefit of the instrumented bag used in this study is that there is no need to 'reset' the bag pre- or post-impact to ensure similar density per strike, which can affect the force-readings in other setups [5]. Nevertheless, the utility of this device within a practical environment remains to be seen since other factors controlled within this study (notably, temperature and water level) could feasibly affect its precision.

The physiological variability of punching kinetics appears to be greater than that of the bag in isolation (i.e., CV = 6.6–13.3%, across various punches [8]), which is promising in providing actionable results for athletes. However, it is worth noting that while the range of values reported in this validation (248–2556 N) are comparable to recreational athletes, impact forces of > 4000 N have been reported in trained boxers [8–10]. While it is unclear how comparable measurements of peak impact kinetics are across different technologies, trained athletes may feasibly exceed the range used in this study. Consequently, while it is possible to infer some probability based on the linearity and low typical error of our analyses, it remains untested whether this same validity and reliability are consistent at higher impact force values. As such, testing variability of athlete scores with this setup is the next logical step in qualifying its utility for practice.

These results, in tandem with the commercial availability and low cost of this device, are promising for the integration of an instrumented water-filled punching bag into practice and research. Nevertheless, since the device is inseparable and indeed relies on a water-filled bag, its uptake within the field could be restricted over more traditional methods of striking training (e.g., foam, fabric, or sand training implements). While outside the scope of this research, whether this method of assessment provides practical utility for the field remains to be seen.

4.1 Limitations

To standardize and control impact momentum, projectile characteristics of the pendulum load against the bag were varied; set in a stationary and standardized condition, which might not reflect its use in common practice (e.g., recurrent human punches to a moving bag). Similarly, static assessment of punching kinetics represents a relatively narrow view of striking, and more generally factors underlying performance in striking sports. Since punching a moving bag will change energy behaviors, measurement precision could be influenced, which would require further investigation. Similarly, the reliability and validity results are relative to the 21" instrumented bag used in this study and may not reflect the consistency and accuracy of other setups (e.g., inter-session). Future research should utilize a direct comparison to a reference system such as an accelerometer or motion capture system to ensure accuracy and consistency across setups. A small proportion of trials were excluded from this analysis due to their status as outliers detected in the preliminary examination of the dataset. This is notable for its use in practice: Some degree of basic outlier analysis to detect and remove values that fall outside the normal range of physiological variability might be warranted; for example, invalid impact force readings likely due to a "double-sloshing' effect of the liquid.

5 Conclusion

Impact kinetics measured by a commercial water-filled bag and integrated pressure sensor appear of sufficient validity and intra-session reliability to provide valuable and actionable information to a range of athletes, practitioners, and researchers.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. No relevant funding was received for this research.

Availability of data and material Data is available upon request.

Code availability Statistical code is available upon request.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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