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# Validity and reliability of a novel impulse-based method to analyse human striking performance

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**ABSTRACT**
We investigated the criterion validity and within- and between-day reliability of a novel method for human striking performance assessment. The Impulse Block Method allows the measurement and calculation of a range of striking variables using a load cell incorporating an impact absorption block and laser gate timer. To assess the criterion validity, we performed repeated drop tests and compared the relationship and agreement between predicted and measured velocity and initial momentum (calculated from impulse) with predicted values using linear regression and Bland-Altman plots (Experiment 1). In Experiment 2, 10 healthy adults performed palm strikes against the Impulse Block on two occasions, and within- and between-day reliability was calculated for impulse, initial momentum, velocity, effective mass, kinetic energy, and power. There was a strong linear relationship and high agreement between measured and predicted velocity and initial momentum (Experiment 1). In Experiment 2, the within- and between-day coefficients of variation were 4.95–10.2% and 6.15–12.1%, respectively, for all variables. Within- and between-day intraclass correlation coefficients were 0.72–0.99 and 0.92–0.99, respectively, for all variables, indicating moderate to excellent reliability. Our findings show that the Impulse Block Method is valid and reliable for analysing a range of striking performance variables in well-targeted and perpendicular linear strikes.

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Combat sports; martial arts; human striking; performance measurement

## Introduction

Striking is the skill of using an extremity of the body or a weapon to gain superiority or inflict damage during combat (Pomerantz, 2018). The ability to optimise striking performance is fundamental to success in combat sports and martial arts and is of great interest to both athletes and coaches (James et al., 2017). Striking performance has typically been measured using peak force and impact velocity (Adamec et al., 2021; Beranek et al., 2020; Dunn et al., 2019; Galpin et al., 2015; Gulledge & Dapena, 2008; House & Cowan, 2015; Neto et al., 2012; Walilko et al., 2005). However, there is a lack of consistency in the range of values recorded. For example, the peak forces of punches vary considerably from < 1000 N to > 5000 N (Galpin et al., 2015; House & Cowan, 2015). This makes it challenging to interpret and compare data between studies and to evaluate the effectiveness of interventions designed to enhance striking performance.

One factor implicated in the measurement error of striking performance is the inherent requirement for the use of padding. Padding is typically positioned between the participant performing the strike and the rigid measurement device (e.g. force plate) to minimise the risk of injury and to allow participants to strike with full force. Because measured peak impact force will change based on the rigidity of the object, any padding placed between the striking limb of the participant and the measurement device will result in an attenuation of peak impact force (Finlay et al., 2023). The extent of this will depend on the thickness and material properties of the padding used (Lenetsky et al., 2022). For example, peak force was reduced by an estimated 35% when impacting a padded target compared to an unpadded target (Atha et al., 1985). Therefore, the measured peak impact force of a strike is a product of the impact event involving both the striker and the object being impacted and thus may not be a true representation of an individual's striking ability. As such, there is a need for alternate measures to improve measurement validity when quantifying striking performance.

Impulse is the integral of force with respect to time and has been used as an alternative to peak force to assess striking performance (Özkaya et al., 2017). Impulse is the change in momentum of an object and can be used to calculate the initial momentum of an impacting object. In contrast to peak force, impulse is unlikely to be influenced by padding placed between the striking limb and the measurement device. This is because the impulse generated when an object's motion is stopped is dependent upon the object's initial momentum before contact and is independent of how the impulse is generated.

The use of an impulse-based method to assess human striking performance can be further enhanced by

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simultaneously recording the impact velocity of the strike. This, in combination with initial momentum of the impacting object, allows the calculation of effective mass or the part of an individual's mass that they are able to contribute to a strike (Neto et al., 2007). Impact velocity and effective mass are fundamental and independent variables which allow for the calculation of the two key dependent variables, kinetic energy and power. During combat, strikes may be modified in various ways to change their impact characteristics and affect the outcome (Neto et al., 2007), and each kinetic variable provides information about different impact characteristics. For example, momentum could provide an indication of the ability to knock an opponent backwards, or to the ground, and can also give an indication of the probability of concussion resulting from a strike to the head (Stojsih et al., 2010). Effective mass may indicate striking competency and has a direct effect on all mass-related kinetic variables (Neto et al., 2007), kinetic energy may indicate the capacity of a strike to inflict damage to an opponent (Quenneville et al., 2011), and power may provide additional information on the probability of injury (Newman et al., 2000). Any single variable is not sufficient to predict the effect that a strike may have on an opponent, and these variables should be analysed in combination to provide optimal performance feedback to athletes.

Importantly, any measures used to evaluate the effectiveness of striking performance must be both valid and reliable. Most studies that have analysed human striking performance have not tested the criterion validity of the equipment or methods used (Adamec et al., 2021; Dunn et al., 2019). Without confirming criterion validity, the extent to which reported values align with real-world measures cannot be determined, and this has likely contributed to the lack of consistency in reported striking performance values. Accelerometer- and linear transducer- based systems are frequently used to analyse striking velocity and other variables, and many of these systems have weak criterion validity or have not been adequately validated (Lambert et al., 2018; Omcirk et al., 2023). Furthermore, the reliability of devices used to assess striking performance varies considerably from poor to excellent (López-Laval et al., 2020; Dunn et al., 2019; Finlay et al., 2023; Harris et al., 2021; Lambert et al., 2018). Therefore, there is a need for improvement in the validity and reliability of methods used to quantify striking performance.

We propose a novel method, termed the 'Impulse Block Method', which could be employed to address the limitations of the use of peak impact force as a primary measure of striking performance, and to measure and calculate key variables associated with striking performance including impulse, initial momentum, impact velocity, effective mass, kinetic energy, and power. The aim of this study was to (i) investigate the criterion validity and within-day reliability of the Impulse Block Method to measure velocity and initial momentum (Experiment 1) and (ii) determine the within- and between-day reliability of the Impulse Block Method to quantify key variables associated with striking performance (Experiment 2).

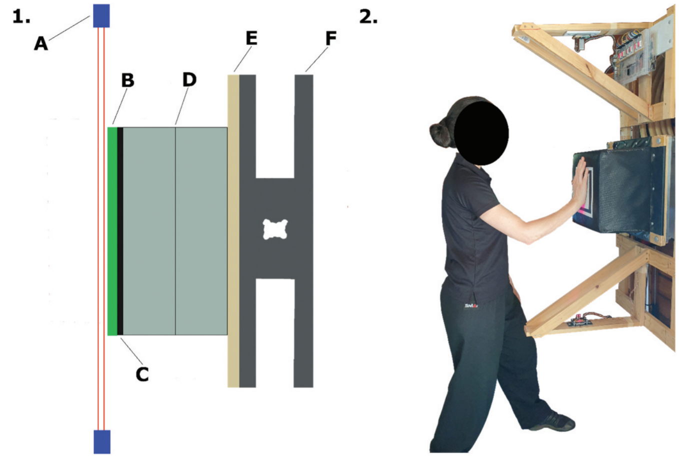


Figure 1. 1. (left hand panel) - impact absorption block incorporating: a) laser gate timer; b) closed cell foam pad; c) G10 fiberglass strike face; d) open cell foam blocks; e) plywood base; and f) a single point load cell. 2. (right hand panel) - participant performing a palm strike against the impulse block.

## Methods

### *The impulse block*

The Impulse Block comprised a single point load cell sampling at 1 kHz (Boxing Training Kit; Loadstar Sensors, Fremont, CA, USA), an impact absorption block, and a bespoke 1 cm gap microsecond laser gate timer positioned in front of the impact absorption block (Figure 1). The impact absorption block consisted of two 300 × 300 x 100-mm open cell foam blocks, an 8-mm-thick G10 fiberglass strike face, and a 10-mm thick closed cell foam pad on a 20-mm thick plywood base, covered by polypropylene mesh fabric secured with a finger-jointed pine collar. The laser gate timer consisted of three basic electronic modules: a laser photogate assembly, a 1-MHz pulse generator (microsecond clock signal), and a digital counter array. The 1-MHz clock signal to the digital counter array was gated by the laser photogate assembly such that the digital counter array started counting when an impacting object broke the first laser beam and stopped counting when the object broke the second laser beam. The beams were positioned 10 mm apart, so the digital counter array counted the number of microsecond (1 MHz) clock pulses that occurred as the object traversed the 10-mm gap. The laser photogate timer was also equipped with a button to reset all three modules for a new impact event. The load cell was connected to a laptop (Satellite L50A; Toshiba, Tokyo, Japan), and force data were captured using software (LoadVUE for Boxer Training; Loadstar Sensors; Fremont, CA, USA).

### *Experiment 1: Validity testing*

#### *Experimental design*

To determine the criterion validity of the Impulse Block Method for the measurements of velocity and initial momentum (calculated from impulse), repeated drop tests of objects with increasing masses were undertaken from different heights. These masses and heights were selected because they would provide velocity and impulse measurements that were within the expected human physiological range for strikes. The Impulse Block was positioned on the floor and a drop test release mechanism, incorporating a quick-release cord, was used that allowed objects to be set at pre-determined heights and dropped from a stationary position.

### Measurement of velocity

To determine the validity of the laser gate timer across a range of velocities, a ring constructed of rattan with an outside diameter of 450 mm, and a thickness of 25 mm was dropped from the following heights: 0.46, 0.82, 1.27, 1.84 and 2.50 m. These heights were selected to result in predicted velocities of 3, 4, 5, 6, and 7 m/s, respectively. The rattan ring was chosen for its light weight and relatively large diameter, which allowed ease of handling and maintenance of optimal orientation. The ring was aligned perpendicularly to the laser gate. To ensure consistency of height and position, the bottom of the ring was aligned with a laser level (LLR-005; Ozito, Bangholme, Australia) secured at each height on a fixed vertical pillar, and the side of the ring was aligned with a spacer attached to the pillar positioning the centre of the ring directly above the laser gate before each drop. Three drops were performed at each height. The time for the ring to cross the 10 mm laser gate was measured and velocity calculated. This measured velocity was compared to the predicted velocity at each height.

### Measurement of impulse and momentum

To determine the validity of the initial momentum measurement (calculated from impulse) across a range of values, repeated drop tests were performed using weights of steel, rubber and/or sand construction with masses ranging from 2 to 30 kg and dropped from heights ranging from 0.5 to 2.5 m (Table 1). Initially, weights of increasing mass were dropped from a height of 0.5 m. Subsequently, heavier objects were dropped at a range of heights to determine the criterion validity for higher energy impacts and different material characteristics. Three drop tests were performed with solid steel weights and a rubber medicine ball at each height. Heights were checked and the position of the object adjusted accordingly before each drop for these tests. Further drop tests were performed with a 7-kg sandbag, and 20- and 30-kg slam balls to analyse the response of the Impulse Block to different materials and heavier objects. For these tests, a single drop test was performed at each of a range of heights, and heights were measured before each drop.

The predicted initial impact velocity for each height was used to calculate the predicted initial momentum of each impacting object (Özkaya et al., 2017). This predicted initial momentum was compared with the measured initial momentum calculated using the following method. The initial momentum of the object was assumed to be transferred to the Impulse Block during the braking phase of the collision, occurring from the point of initial contact of the object with the Impulse Block to the point at which the velocity of the object reached zero. To determine the impulse during the braking phase, the total impulse was calculated using numerical integration. The sum of the force samples was calculated during the period when the object was in contact with the force plate, and then this sum was multiplied by the sampling period (the inverse of the sampling frequency). This value was then divided by two to calculate the initial momentum, based on the following assumption. Due to the complex nature of the force–time curves captured by the Impulse Block system and to allow ease of calculation, the initial momentum was approximated to be half of the change in momentum, as would occur in a perfectly elastic collision (Özkaya et al., 2017). To confirm this assumption, in a subset of trials using the medicine ball, slow motion video footage (960 frames/s) was captured and used to measure the time at which the velocity of the medicine ball reached zero. The mean time from the point of contact to the point at which the velocity of the ball reached zero was 47.8 ± 0.24% of the full duration of the force–time curve, which satisfied our assumption to use the impulse during the first half of each collision to calculate the initial momentum for the remainder of this study. This calculated initial momentum value was compared with the predicted initial momentum value which was calculated based on the mass and height of each drop test that was performed.

### Statistical analysis

Statistical analyses were performed using Excel (Version 2205; Microsoft, Redmond WA, USA), PAleontological STatistics software (Version 4.03; Øyvind Hammer, Oslo, Norway) and the web tool Huygens-Science BA-plotterR (https://huygens.science.uva.nl/BA-plotteR/) (Goedhart & Rishniw, 2021). Linear regression and Bland-Altman plots were used to determine the strength of relation and agreement, respectively, between predicted and measured velocities and initial momentums from the repeated drop tests (Bland & Altman, 1986). Statistical significance was set at $p < 0.05$. Coefficients

**Table 1.** Mass characteristics and heights of each drop test performed. x indicates whether the test was performed for a given object at a given height.

| Object (construction) | Mass (kg) | Height (m) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 0.5 | 0.7 | 1.0 | 1.3 | 1.5 | 1.6 | 2.0 | 1.8 | 2.5 |
| Weight (solid steel) | 2 | x | | | | | | | | |
| | 3 | x | | | | | | | | |
| | 4 | x | | | | | | | | |
| | 5 | x | | | | | | | | |
| Medicine Ball (rubber) | 7 | x | | x | | x | | x | | x |
| Sandbag (sand) | 7 | x | | x | | | | x | | |
| Slam Ball (rubber and sand) | 20 | | x | x | | x | x | | x | |
| | 30 | | | | x | | | | | |

of variation (CV) (for the steel weights and rubber medicine ball drop tests only) and intraclass correlation coefficient (ICC (3,1)) (for all drop tests) were used to determine within-day reliability. CVs were not calculated for the sandbag and slam ball drop tests as only a single drop test was performed at each height for these tests.

## Experiment 2: Reliability testing

### Participants

A convenience sample of 10 healthy young adults were recruited from South-East Queensland, Australia via an approved media campaign that incorporated physical advertisement via media releases and social media. A self-reporting medical history questionnaire was used to confirm that participants were free from illness and injury (Exercise & Sports Science Australia, 2023). All participants provided written, informed consent before participating in the study. All study procedures were approved by the University of Southern Queensland Human Research Ethics Committee (H22REA062) that adheres to the Declaration of Helsinki. Participant characteristics of the study cohort are shown in Table 2.

### Experimental design

Participants attended the research laboratory for three visits on three separate days. Visit 1 was a familiarisation session and Visits 2 and 3 were data collection sessions. The visits were conducted a minimum of two and a maximum of 7 days apart. During the familiarisation session (Visit 1), body mass and standing height were measured using an electronic scale (HBF-514C; Omron, Kyoto, Japan), and custom-made wall-mounted stadiometer. Subsequently, participants were instructed to stand in front of the Impulse Block with their feet approximately hip width apart and one foot closer to the striking surface than the other (staggered combat stance). The Impulse Block was mounted on a wall with the base of the block at a height of 1.07 m (Figure 1). This height was based on the mean of the standing height of participants and allowed all participants to perform the strikes comfortably. Participants then performed a sequence of palm strikes. The palm strike was chosen for this study as this type of strike required less familiarisation and could be performed with less risk of injury by untrained participants compared to a punch (Beranek et al., 2022). Participants positioned themselves at a distance from the Impulse Block that was most comfortable to them. When the participant had familiarised themselves with the palm strikes to be performed and were in a comfortable stance, a distance measurement was taken from the front of their lead foot to the base of the wall underneath the Impulse Block. This measurement was used to ensure that the participant's position relative to the Impulse Block remained the same throughout the testing. At each testing session (Visits 2 and 3) and following a warm-up of 7–10 palm strikes, participants were instructed to strike as hard as they could and perform three palm strikes with their dominant hand with 30 s of rest between each strike. A limited sample of three maximal strikes was used. This number was chosen to minimise the effect of fatigue on performance variability, and our primary aim was to determine the reliability of the Impulse Block to quantify striking performance variables, rather than the reliability of repeated palm striking. Identical procedures were performed in Visits 2 and 3 to assess the between-day reliability.

Table 2. Participant ($n = 10$) anthropometrics, minutes of physical activity per week and training status. Values are mean ± SD.

| | |
|---|---|
| Age (years) | 32 ± 9 |
| Sex (Male/Female) | 3/7 |
| Height (m) | 1.71 ± 0.08 |
| Body mass (kg) | 77.2 ± 21.6 |
| Body mass index (kg/m$^2$) | 26.3 ± 6.58 |
| Self-reported physical activity (MET: min/week) | 439 ± 350 |
| Experience (Martial arts trained/Martial arts untrained) | 7/3 |

MET, metabolic equivalent.

### Measurement and calculation of variables

For each palm strike, the time was recorded from the microsecond laser gate timer, and velocity calculated. Impulse and initial momentum was calculated from the load cell data as described in Experiment 1 above (see *Measurement of Impulse and Momentum*).

The effective mass, which is that part of a human's mass that is applied during a strike (this is typically a small percentage of the total body mass) was calculated using the following equation:

$$\boldsymbol{m_e} = \frac{\overrightarrow{\boldsymbol{p}_1}}{\overrightarrow{\boldsymbol{v}_i}} \tag{1}$$

where $m_e$ represents effective mass, $\overrightarrow{p_1}$ represents initial momentum, and $\overrightarrow{v_i}$ represents the velocity of the hand at the point of impact.

Kinetic energy was calculated by the equation:

$$\boldsymbol{E_k} = \frac{1}{2}\boldsymbol{m_e} \times \overrightarrow{\boldsymbol{v}_i}^2 \tag{2}$$

where $E_k$ represents kinetic energy, $m_e$ represents effective mass, and $\overrightarrow{v_i}$ represents the velocity of the hand at the point of impact.

Power was calculated by the equation:

$$\boldsymbol{P} = \frac{\Delta \boldsymbol{E_k}}{\boldsymbol{t_i}} \tag{3}$$

where $P$ represents power, and $t_i$ represents the impact duration of braking phase of the force–time curve. This time represents the time over which work is applied by the Impulse Block onto the limb to cause a change in energy (from $\overrightarrow{v_i}$ to the point where the velocity of the hand reached zero) and is approximated as half of the total time of the force–time curve, as described in Experiment 1 above (see *Measurement of Impulse and Momentum*).

### Statistical analysis

Statistical analyses were performed using Excel (Version 2205; Microsoft, Redmond WA, USA) and PAleontological STatistics software (Version 4.03; Øyvind Hammer, Oslo, Norway) to determine within- and between-day reliability for all measured and calculated key variables, which included initial momentum, velocity, effective mass, kinetic energy, and power. Within-day reliability was assessed using the mean within-participant CV and ICC (3,1) (Koo & Li, 2016). Between-day reliability was assessed by mean within-participant CV and ICC (3,k) with 95% upper and lower bound confidence intervals (95% CI). The guidelines provided by Koo and Li (Koo & Li, 2016) were used to determine the strength of the ICCs, with below 0.5 defined as poor, between 0.5 and 0.75 defined as moderate, between 0.75 and 0.9 defined as good, and above 0.9 defined as excellent. All data were checked for normality using the Shapiro–Wilk test and were classified as normal. Statistical significance was set at $p < 0.05$. Results are presented as mean ± standard deviation (SD) unless stated otherwise.

## Results

### Experiment 1: Velocity

There was a strong, linear relationship between the measured and predicted velocities ($r = 0.998$, $p < 0.001$; Figure 2). The Bland-Altman plot (Figure 3) indicates that the agreement between the predicted and measured velocity falls within 2SD of the mean of the predicted and measured velocity for all except for one data point. There was a random variability in the difference between the predicted and measured velocity. The mean within-day CV of the measured velocity at each height was 1.5%. The ICC (3,1) of the measured versus predicted velocity was 1.0 [1.0, 1.0] showing excellent within-day reliability.

### Experiment 1: Impulse and momentum

There was a strong, linear relationship between measured initial momentum (calculated from impulse) and the predicted initial momentum values across the range of drop tests ($r = 0.997$, $p < 0.001$; Figure 4). The Bland-Altman plot (Figure 5) demonstrated that the agreement between the predicted and measured initial momentum falls within 2SD of the mean of the predicted and measured initial momentum. There was a random variability in the difference between the predicted and measured initial momentum.

The within-day CV of the measured initial momentum at each height for the steel weight and rubber medicine ball drop tests was between 0.36% and 1.75%. The ICC (3,1) of the measured versus predicted initial momentum was 0.99 [0.99, 0.996] showing excellent within-day reliability.

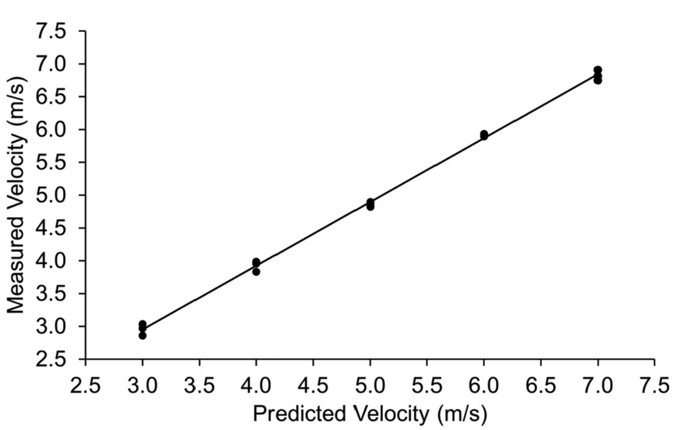


Figure 2. Linear regression of predicted and measured velocity.

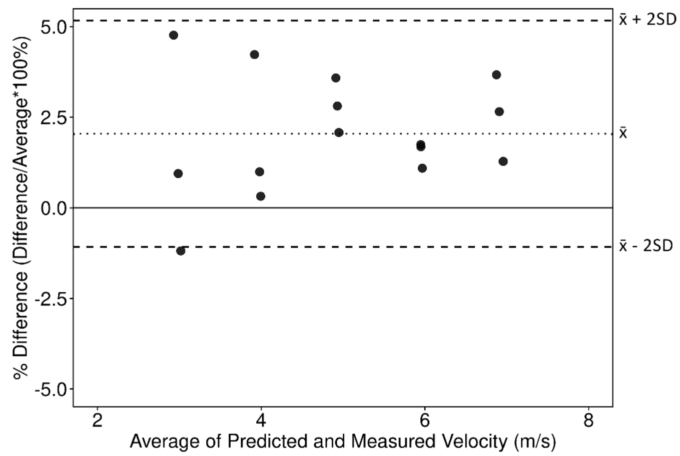


Figure 3. Bland-Altman plot of the % difference between the predicted and measured velocity vs. The average of the predicted and measured velocity.

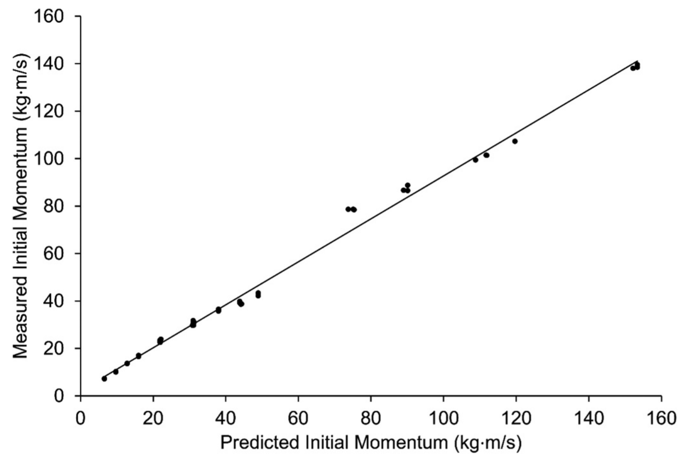


Figure 4. Linear regression of measured and predicted initial momentum.

### Experiment 2: Reliability of palm striking measurement

The within-day CV was 4.95–10.2% for all variables (Table 3). The between-day CV was 6.15–12.1% for all variables. The within-day ICCs were 0.72–0.99 for all variables indicating moderate to excellent within-day reliability. The between-day ICCs were 0.92–0.99 for all variables indicating excellent between-day reliability.

## Discussion

### Main findings

The aim of this study was to (i) investigate the criterion validity and within-day reliability of the Impulse Block Method to measure velocity and initial momentum (Experiment 1) and (ii) determine the within- and between-day reliability of the Impulse Block Method to quantify key variables associated with striking performance (Experiment 2). We found a strong

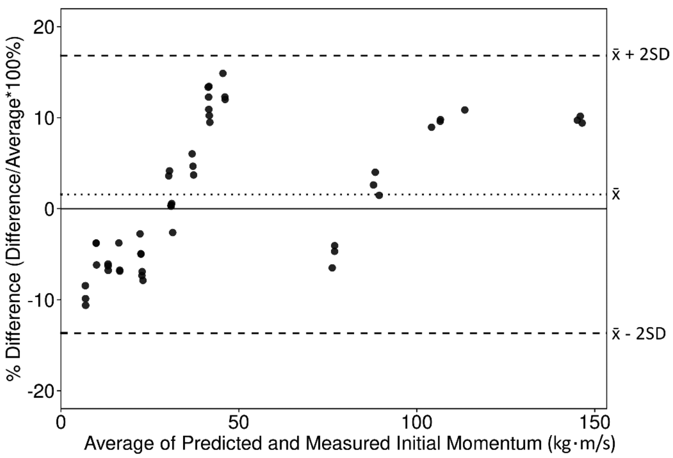


Figure 5. Bland-Altman plot of the % difference between the predicted and measured initial momentum vs. The average of the predicted and measured initial momentum.

linear relationship and high agreement between measured and predicted values for velocity and initial momentum (calculated from impulse) in Experiment 1. The measured values also had excellent within-day reliability. A moderate to excellent within-day reliability and excellent between-day reliability was observed for all measures associated with striking performance in Experiment 2. Our findings show that the Impulse Block Method is a valid and reliable method for analysing a range of key striking performance variables in well-targeted, perpendicular linear strikes and implications of these findings are discussed below.

## Criterion validity

Experiment 1 found a strong linear relationship and high agreement between the predicted and measured velocity and initial momentum (Figures 2–5). This demonstrates that the Impulse Block Method provides valid measurement of velocity and initial momentum. Given that most studies that have analysed human striking performance have not tested the criterion validity of the equipment or methods used, comparison between studies is difficult (Adamec et al., 2021; Dunn et al., 2019). Furthermore, accelerometer- and linear transducer- based systems are frequently used to analyse striking velocity and other variables, but many of these systems have weak criterion validity or have not been adequately validated (Lambert et al., 2018; Omcirk et al., 2023). The Impulse Block Method provides a solution to this problem as a method of analysing human striking resulting in valid measurements of initial momentum, impulse, and velocity, and the additional variables that can be calculated from these variables, namely effective mass, kinetic energy and power.

## Reliability

The Impulse Block Method provided excellent between-day reliability and good to excellent within-day reliability for all measurements except velocity. Given that the microsecond timer display was visible to participants, it is possible that the moderate reliability of the velocity measurements (ICC (3,1) on Visit 3 = 0.72) may have been due to participants modifying the velocity of subsequent strikes in an attempt to improve their score. We recommend that the testing set up be revised in future iterations so that participants are blinded to all measured values during testing. Improved reliability in measurement is necessary because the reliability of devices used to measure velocity during striking has been shown to vary considerably depending on the technologies employed. For example, previous studies investigating the reliability of linear position transducers and accelerometer-based punching trackers to measure the velocity of punches have reported weak to excellent within- and between-day device reliability (López-Laval et al., 2020; Harris et al., 2021; Lambert et al., 2018).

The reliability of other striking performance outcome variables, such as impulse and peak force, has previously been measured with a load cell. The within-day CV of the impulse and peak force of punches measured by a padded load cell during a 3-min punch test performed on 2 days by highly trained male amateur boxers were 3.9–17.2%, demonstrating poor between-day reliability (Dunn et al., 2019). Another study using a vertically mounted padded force plate to quantify the peak punch force of amateur boxers reported excellent within-day and good to excellent between-day reliability for peak punch impact force (Finlay et al., 2023). This is similar to the results of the current study, which could be due to the use of a load cell in both methods. To our knowledge, there are no studies that have assessed the reliability of the other variables reported in the current study, including effective mass, kinetic energy and power, suggesting that the Impulse Block method is the only known reliable method of assessing effective mass, kinetic energy and power as they relate to striking performance.

## Comparison of measurements from the impulse block method to other studies

The analysis of key variables associated with striking performance, including impulse, initial momentum, velocity, effective mass, kinetic energy, and power, can provide a more comprehensive analysis of striking performance than peak force alone. While studies that have analysed the validity and/or reliability of effective mass, kinetic energy, and power are lacking, several studies have incorporated these variables in the analysis of human striking (Adamec et al., 2021; Neto et al., 2007, 2012; Wasik & Nowak, 2015). These studies employed a variety of methods, resulting in considerable variation in values obtained. For example, Adamec et al. (2021) reported that the impulse and effective mass of palm strikes were lower, and velocity was higher than reported in the present study. Neto et al. (2007) reported similar effective mass values from forward palm striking to the present study. Finally, Wasik & Nowak (2015) reported much higher kinetic energy values of straight forward punches than in the present study, which appear to be well outside of the expected range for human striking (Harruff et al., 2013). These studies highlight the considerable variation in measured values in the measurement and

Table 3. Within- and between-day mean ± standard deviation (SD), mean within-participant coefficients of variation (CV), interclass correlation coefficients (ICCs) and 95% confidence intervals (CI) of measurements during palm striking.

| | Data Collection Visit 1 | | | | Data Collection Visit 2 | | | | Between Visits | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean ± SD | CV (%) | ICC (3,1) | 95% CI | Mean ± SD | CV (%) | ICC (3,1) | 95% CI | Mean ± SD | CV (%) | ICC (3,k) | 95% CI |
| Impulse, N·s | 33.5 ± 20.3 | 7.31 | 0.99 | [0.96, 1] | 31.0 ± 19.3 | 4.95 | 0.99 | [0.98, 1] | 32.2 ± 19.7 | 10.1 | 0.98 | [0.94, 1] |
| Initial Momentum, kg·m/s | 16.8 ± 10.2 | 7.31 | 0.99 | [0.96, 1] | 15.5 ± 9.7 | 4.95 | 0.99 | [0.98, 1] | 16.1 ± 9.84 | 10.1 | 0.98 | [0.94, 1] |
| Velocity, m/s | 5.92 ± 0.81 | 5.10 | 0.80 | [0.54, 0.94] | 6.09 ± 2.3 | 6.57 | 0.72 | [0.39, 0.91] | 6.04 ± 0.9 | 6.15 | 0.97 | [0.86, 0.99] |
| Effective Mass, kg | 2.72 ± 1.49 | 8.37 | 0.97 | [0.92, 0.99] | 2.56 ± 1.52 | 8.11 | 0.97 | [0.92, 0.99] | 2.64 ± 1.50 | 11.2 | 0.98 | [0.91, 1] |
| Kinetic Energy, J | 52.4 ± 35.8 | 9.90 | 0.98 | [0.94, 0.99] | 48.1 ± 31.7 | 7.77 | 0.97 | [0.92, 0.99] | 50.2 ± 34.2 | 12.1 | 0.99 | [0.95, 1] |
| Power, W | 843 ± 217 | 10.2 | 0.83 | [0.58, 0.95] | 879 ± 265 | 8.82 | 0.87 | [0.67, 0.96] | 861 ± 241 | 11.7 | 0.92 | [0.68, 0.98] |

calculation of effective mass, kinetic energy, and power, demonstrating the importance of establishing criterion validity and consistent methodology for any methods employed to analyse human striking. We propose that the Impulse Block Method be adopted in future studies as a valid and reproducible method to assess these variables.

### *Limitations and potential expansions of the impulse block method*

While the drop tests used in Experiment 1 were the most accessible and direct method available to assess the criterion validity of the key kinetic variables measured and calculated using the Impulse Block Method, there are some limitations involved in the use of drop tests. As described in the Methods section above, to allow ease of calculation, the Impulse Block Method involves an approximation, assuming that the initial momentum is equal to half of the change in momentum, as would occur if the collision was perfectly elastic (Özkaya et al., 2017). While this assumption was found to be accurate for a sample of drop tests, the duration of the braking phase and the point at which the velocity of the impacting object reaches zero before re-bounding will vary depending on the height, mass and kinetic energy transferred into the Impulse Block system. This is because the Impulse Block system consists of a complex differentially dampened spring system including the constrained foam block and metallic spring of the load cell, which is not a perfect mechanical spring. This could account for some of the lack of agreement between the predicted and measured variables, however this limitation is specifically related to the Impulse Block's intrinsic energy-dependent reaction to drop tests. This can be confirmed in future studies by implementing a more complex testing system to transfer known impulses to the Impulse Block. As the strikes employed in Experiment 2 involved impacting the surface of the Impulse Block at an angle close to horizontal, we do not envisage that these strikes would result in a greater error in comparison to the error encountered in the drop tests.

It should be noted that the impacts and strikes employed in this study were linear impacts targeting the centre of the device perpendicularly to its surface. Other types of strikes or testing conditions could include different vector directions and impact locations. As such, systematic mechanical and human tests with different vector directions and impact locations should be conducted to confirm the reliability of the method under those conditions. However, because the impulse generated when an object's motion is stopped is dependent upon the object's initial momentum before contact and is independent of how the impulse is generated, the tolerance for off-centre impacts in an impulse-based measurement system is expected to be higher than in a system based on peak impact force. For non-linear or rotational strikes (e.g. circular punches or roundhouse kicks), it is proposed that the Impulse Block be constructed so that the angle of the striking surface can be adjusted to allow non-linear or rotational strikes to impact the striking surface perpendicularly, minimising the potential effect of these strikes on the reliability of the system.

Another limitation of the study is the number of strikes sampled in Experiment 2. We elected to limit the number of strikes to three per participant, to reduce the effect of fatigue on subsequent strikes. This allowed us to more accurately assess the reliability of the strikes by ensuring participants were consistently in the same physiological state (i.e. not fatigued). The small number of strikes may have reduced our statistical power; however, we were still able to observe moderate-high ICC values with a relatively small 95% CI range. As such, we are confident that our sample of strikes is sufficient to assess the reliability of the system to accurately measure striking performance in this context. Whilst the aim of the present study was to determine the reliability of the Impulse Block to quantify striking performance variables, further research should be undertaken to quantify the reliability of the Impulse Block to measure many repeated strikes.

There are a range of methods available to analyse human striking performance that have been investigated and the variables reported from these typically include peak force and impact velocity (Adamec et al., 2021; Atha et al., 1985; Beranek et al., 2020; Dunn et al., 2019; Galpin et al., 2015; Gulledge & Dapena, 2008; House & Cowan, 2015; Neto et al., 2008). As discussed in the introduction of this study, there are considerable limitations to the use of peak force when analysing and comparing striking performance. Although our results demonstrate that the Impulse Block Method is a valid and reliable method for analysing a range of key striking performance variables, for studies where peak force measurements are required, the Impulse Block method could also be expanded to include a standardised method of calculating an estimated peak force. This could be achieved by fitting the impulse data from a strike to a standardised 'impacting object specific' force–time curve. This would enhance the ability to compare between studies via facilitating the comparison of peak force across different measurement set-ups.

## Conclusion

The aim of this study was to (i) investigate the criterion validity and within-day reliability of the Impulse Block Method to measure velocity and initial momentum (Experiment 1) and (ii) determine the within- and between-day reliability of the Impulse Block Method to quantify key variables associated with striking performance (Experiment 2). There was a strong linear relationship between measured and predicted values for velocity and initial momentum, and both variables showed high agreement between predicted and measured values. The Impulse Block Method provides moderate to excellent within- and between-day reliability for a comprehensive range of key kinetic variables during palm striking in healthy adults. Our findings show that the Impulse Block Method is a valid and reliable method for analysing striking performance in well-targeted, perpendicular linear strikes. The Impulse Block Method also enables the measurement and calculation of variables, which provide additional insight into the potential effects of an individual's strike beyond what can be gained from peak impact force or impact velocity alone. Further research is required to confirm the reliability of the method for different types of strikes in a variety of real-world conditions.

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S.W., L.W., B.H., D.E.M., conceived and designed the experiments; S.W., L.W., D.E.M., performed the experiments; S.W. analyzed and interpreted the data, L.W., B.H., C.C., D.E.M. assisted in interpreting the data, S.W. developed the first full draft of the manuscript and approved the final version of the manuscript. L.W., B.H., C.C., D.E.M. provided substantial feedback on versions of the manuscript, and approved the final version of the manuscript.

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