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Response to Reviewers:	The authors are grateful for the positive feedback provided on their original manuscript and are happy to revise it in line with the suggestions made by the reviewer. Specifically: 1. "I'm happy with the definition of contact but feel the definition of initiation and recovery based on "guard position" is open to some interpretation. It would help to have an intra-observer comparison of identification of these times for a subset of the data to have some idea of the reliability of this part of the data collection." Response: We have added an analysis of the intra-observer reliability (Table 1 and accompanying text on pp. 9-10 of the revised submission) as requested and are content that this important measurement pre-requisite was established, thereby reinforcing the validity of the data reported. 2. "All diagrams will need to be done and be understandable in black and white." Response. This has been done. 3. "Use SI units throughout eg replace seconds with s." Response. This has been done. 4. "In the results include the degrees of freedom (main effect and error) with the F ratios." Response. This has been done. 5. "Where p < 0.05 give the actual p value - it would be interesting to know if a

	significant result was just significant or highly significant. "$p < 0.05$" involves a little too much information loss." Response. This has been done. We hope that the manuscript is now acceptable for publication. Regards. Prof. Kevin Lamb

An analysis of the three-dimensional kinetics and kinematics of maximal effort punches among amateur boxers

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Abstract

The purpose of this study was to quantify the 3D kinetics and kinematics of six punch types among amateur boxers. Fifteen males (age: 24.9 ± 4.2 years; stature: 1.78 ± 0.1 m; body mass: 75.3 ± 13.4 kg; boxing experience: 6.3 ± 2.8 y) performed maximal effort punches against a suspended punch bag during which upper-body kinematics were assessed via a 3D motion capture system, and ground reaction forces (GRF) of the lead and rear legs via two force plates. For all variables except elbow joint angular velocity, analysis revealed significant (P < 0.05) differences between straight, hook and uppercut punches. The lead hook exhibited the greatest peak fist velocity (11.95 ± 1.84 m/s), the jab the shortest delivery time (405 ± 0.15 ms), the rear uppercut the greatest shoulder joint angular velocity (1069.8 ± 104.5 deg/s), and the lead uppercut the greatest elbow angular velocity (651.0 ± 357.5 deg/s). Peak resultant GRF differed significantly (P < 0.05) between rear and lead legs for the jab punch only. Whilst these findings provide novel descriptive data for coaches and boxers, future research should examine if physical and physiological capabilities relate to the key biomechanical qualities associated with maximal punching performance.

Key words: combat sports, boxing, punching, technique analysis.

Introduction

Boxing punches are intricate actions requiring the recruitment of leg, trunk and arm musculature to function synergistically in a coordinated manner (Turner, Baker & Miller, 2011). Despite the importance of punching to successful performance, there is only a limited amount of biomechanical knowledge for most of its techniques. Some kinematic characteristics (such as joint angles and velocities and punch velocity) have been investigated for certain punches (jabs, rear-hand crosses, lead hooks, rear hooks and rear uppercuts: Cabral et al., 2010; Cheraghi et al., 2014: Kimm & Thiel, 2015; Piorkowski et al., 2011) among competitive boxers. For example, research has reported the delivery times and fist velocities of straight (357 ± 178 ms and 5.9 m/s – 8.22 m/s) and hook (477 ± 203 ms and 8 m/s – 11 m/s) punches, respectively (Cheraghi et al., 2014; Kimm & Thiel, 2015; Piorkowski et al., 2011; Whiting et al., 1988).

Joint and punch velocities are dependent upon a proximal-to-distal sequencing pattern initiated by the lower limbs that travels distally through the pelvis, trunk and arm before peaking at the fist, causing the acceleration of the fist towards the target (Cheraghi et al., 2014). Proximal-to-distal sequencing and the subsequent velocities generated via rapid joint rotations have been observed in various punching and kicking techniques across combat sports (Estevan, Falco, Silvernail & Jandacka, 2015; Sorensen, Zacho, Simonsen, Dyhre-Poulsen & Klausen, 1996; VencesBrito, Rodrigues Ferreira, Cortes, Fernandes & Pezarat-Correia, 2011). Fist velocity has also been suggested to be dependent upon the distance of the acceleration path to the target, with hook punches exhibiting greater values than straight punches due to a longer acceleration pathway that facilitates the generation of greater pre-impact fist velocities (Piorkowski et al., 2011; Viano et al., 2005; Whiting et al., 1988). However, how joint and fist velocity differ between straight, hooks and uppercuts has not been reported within the scientific literature.

Kinetic characteristics have also been shown to influence properties of punching, particularly ground reaction forces (GRF) (Mack, Stojsih, Sherman, Dau & Bir, 2010; Yan-ju, Yi-gang, Yan & Zheng-Ping, 2013). For example, the force generated by the rear leg has been suggested to contribute considerably to the performance of rear hand punches (Cheraghi et al., 2014; Filimonov et al., 1985; Turner et al., 2011), whilst Yan-ju et al. (2013) noted that lead leg force was a significant contributor to jab fist velocity. However, Mack et al. (2010) reported small, albeit significant, relationships between lower body forces and peak hand velocity for rear hook (R^2 = 0.103) and rear-hand cross (R^2 = 0.099) punches, respectively, suggesting that further research is warranted here. Moreover, whilst their relevance has been alluded to (Lenetsky et al, 2013), no scientific studies have examined the directional (anteroposterior, mediolateral, vertical) application of GRF during specific punch types.

With the general lack of empirical evidence, coaches and boxers are unlikely to have the means to form an understanding of how punches can be enhanced through kinetic and kinematic assessments and how knowledge and information quantified via such assessments can influence performance. In the manner of previous appraisals of sports techniques (Kageyama, Sugiyama, Takai, Kanehisa & Maeda, 2014; Torres, 2013; Wagner et al., 2014), gathering information relating to fist velocity, GRF production and their relationship across different punch techniques could facilitate a grasp of the technical intricacies of different punch techniques and lead to the development of punch-specific training interventions.

The overall aim of this study therefore was to quantify the GRF and kinematic characteristics of a variety of maximal punches among amateur boxers. The main objectives were to: (i) assess peak fist velocities and delivery times across punch types; (ii) examine the differences in lead and rear leg resultant GRF and its directional application across punch types; (iii) quantify lead leg net braking, rear leg net propulsive and lead and rear leg vertical impulse across punch types, and (iv) quantify the relationships between kinematic (punch delivery time, peak shoulder joint resultant angular velocity, peak elbow joint resultant angular velocity) and kinetic (peak lead and rear leg resultant GRF, lead leg net braking and vertical impulse, rear leg net propulsive and vertical impulse) variables and peak resultant fist velocity.

Methods

Participants

Fifteen males (age: 24.9 ± 4.2 years; stature: 1.78 ± 0.1 m; body mass: 75.3 ± 13.4 kg; years of experience: 6.3 ± 2.8 years) across seven weight categories (flyweight to super-heavyweight) were recruited from six amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts). A sample size calculation (G*Power version 3.1.9, Universität Düsseldorf, Dusseldorf, Germany - Faul et al., 2009) based on standard input parameters (α level = 0.05, power = 0.8) and effect sizes (0.68 for punch delivery time and 0.99 for contact speed) gleaned from Piorkowski et al. (2011), yielded a sample of 12. All participants provided written informed consent prior to the study and institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee.

Design

The study adopted a within-subjects design to assess kinetic and kinematic aspects of straight, hook and uppercut punches, considered to represent the principal techniques observed in boxing competition (El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). All data were collected in one session and participants did not require a separate familiarisation trial as all had experience (≥ 2 years) performing the punch techniques and were familiar with punching a target similar to that used in the present study. Four kinematic and six kinetic variables were measured with respect to the six punch types via a 3D motion capture system and two embedded force platforms, respectively.

Procedures

For all punch trials, a water-filled punch bag that resembled the average height of a human head (9 in) (Aqua Bag 'Headhunter' model, Aqua Training Bag, New York, United States) was used to provide a striking target (see Figure 1). Utilising a punch target that moves upon impact has been advocated (Atha et al., 1985; Nakano, Lino, Imura & Kojima, 2014) as an effective way of ensuring maximal effort punches. The punch bag was suspended at the shoulder level of each participant by a heavy duty steel chain secured by a punch bag hook located above the designated testing area. Three reflective markers were placed on the top of the punch bag in order to permit the 3D cameras to detect its movement upon impact. This movement acted to verify the instance of punch contact (see Figure 2).

[Figures 1 & 2 about here]

Seventy six reflective markers were placed on specific anatomical landmarks of each participant to facilitate a comprehensive assessment of full-body kinematics in 3D spaces across six degrees of freedom (see Figure 3). Of the 76 markers, 18 were utilised for calibration purposes only and were removed during the dynamic trials. With the exception of the head (not required for analysis) and the addition of hand segments (Figure 3) in the manner of Piorkowski et al. (2011) (to obtain detailed fist velocity data), the defined body segments for all punch trials corresponded with those used by Vanrenterghem, Gormley, Robinson and Lees (2010). These segments included the upper arm (left and right), lower arm (left and right), thorax, pelvis, upper leg (left and right), lower leg (left and right), and foot (left and right). Markers allocated to the ‘radial wrist’, ‘ulnar wrist’ and ‘glove centre’ defined the hand segment (see Figure 4).

[Figures 3 & 4 about here]

The 3D positions of all reflective markers were obtained from eight infrared, opto-electric ceiling mounted cameras (Oqus 7+ system, Qualisys Inc., Gothenburg, Sweden). Kinematic data was obtained via Qualisys Track Manager (QTM) (Version

2.14, Qualisys Inc., Gothenburg, Sweden) and subsequently analysed using Visual 3D (Version 6, C-Motion Inc., Rockville, United States). All marker data were filtered using a low-pass Butterworth filter with a cut-off frequency of 12 Hz prior to and after the computer link-model based data had been generated to reduce the potential noise in the signal, as suggested in previous boxing-related research (Piorkowski et al., 2011). This cut-off frequency was deemed appropriate following pilot work whereby discrepancies in data were visually inspected for unwanted signal noise. The same data processing methods were implemented across the data-set, meaning any potential errors were consistent.

GRF data were collected from both the lead and rear legs of each participant for all punch trials by two embedded force platforms (model 9281CA with 600 x 400 mm internal amplifiers, Kistler Instruments, Hampshire, UK). GRF data were low-pass filtered using a 4th-order Butterworth filter with a cut-off frequency of 100 Hz based on the recommendations of Bezodis, Salo and Trewartha (2011).

Prior to testing, participants completed a 10 min self-selected warm-up comprising generic and boxing-specific activities such as jogging, dynamic stretches and shadow-boxing (Smith et al., 2000). The boxers were permitted to strike the punch bag whilst wearing the reflective markers until they became familiarised with the set up and positioning of the target (~5 min). All were instructed to strike the punch bag using a single, maximum effort punch (termed as a ‘knock-out’ punch) whilst maintaining the correct technique for the specific punch type performed. Boxers wore fabric hand-wraps (450 cm length, 5 cm width; Adidas, Germany) and boxing gloves (284 g; Adidas, Germany) as required during competition.

Six punch types (jab, rear-hand cross, lead hook, rear hook, lead uppercut, rear uppercut) were performed from either an orthodox (left foot leading) or southpaw (right foot leading) stance (Hickey, 2006), depending on the preference of each participant (orthodox *n* = 11; southpaw *n* = 4). Each punch was performed five times in succession with 60 s recovery period between trials. In the manner of previous related research (Lenetsky, Brughelli, Nates, Cross, & Lormier, 2017), all punches were performed in groups per each punch types in the order of (1) jab; (2) rear-hand cross; (3) lead hook; (4) rear hook; (5) lead uppercut and; (6) rear uppercut. Performance feedback was not provided during the testing procedures.

Data processing

Kinematic and GRF data was analysed via Qualisys Track Manager (QTM) (version 2.14, Qualisys Inc., Gothenburg, Sweden), whereby reflective markers and anatomical landmarks were labelled. Thereafter, punch trials were exported to Visual 3D (Version 6, C-Motion Inc., Rockville, United States) from which full-body joint segments and key events were created alongside the calculation of kinematic and GRF data. Key events (see below) were identified from visual observations due to the differing technical intricacies and punch set-ups across each individual participant (e.g. a hook punch performed directly from the guard versus a hook punch thrown from a ‘bobbing and weaving’ motion). These events were classified as: (i) INITIATION (the initiation of a countermovement prior to the fist being projected towards the punch target), identified from the descent of the hand segment markers on the punching hand along the longitudinal axis; and (ii) CONTACT (one frame prior to the fist impacting the punch target), identified from the initial movement of the markers located on the punch target. These event labels were subsequently used to export kinematic and GRF data in ASCII formats to be further analysed in Microsoft Excel (Microsoft Corporation, Reading, UK).

The kinematic variables computed from the punch data were: punch delivery time from event markers INITIATION to CONTACT, peak resultant fist velocity of the hand segment (defined from ‘radial wrist’, ‘ulnar wrist’, ‘knuckle 1’, and ‘knuckle 5’ tracking markers) from INITIATION to CONTACT, peak resultant shoulder joint angular vector velocity (shoulder joint defined from upper arm tracking markers relative to the defined thorax/ab segment) from INITIATION to CONTACT, and peak resultant elbow joint angular vector velocity (elbow joint defined from the upper arm and forearm tracking markers) from INITIATION to CONTACT. Peak joint velocity timings were quantified from the moment of peak angular joint velocity (shoulder and elbow) from punch data normalised to 101 data points.

The kinetic variables computed from the punch data were: peak lead leg resultant GRF, peak rear leg resultant GRF, total lead leg net braking impulse, lead leg vertical impulse, total rear leg net propulsive impulse, and total rear leg vertical impulse (all from INITIATION to CONTACT). All GRF data (peaks and impulses) were normalised to participants’ body mass (N/kg).

INITIATION key event identification

The instant of INITIATION for each punch type was subject to test-retest intra-observer reliability testing. For each punch type, ten trials were randomly selected for analysis with the time between force plate contact (recorded objectively by the Kistler platforms) and punch initiation (determined by the lead researcher) recorded in

Visual 3D. Analysis revealed INITIATION identification was consistent across punch trials, with low typical error (Hopkins, 2000), low CV% (Roberts & Priest, 2006), and narrow limits of agreement (Bland & Altman, 1999) observed for each punch type (see Table 1). Consequently, the reliability of punch INITIATION was deemed acceptable given the variation was unlikely to have had a meaningful impact upon the interpretation of the dependent variables (i.e. punches remained distinguishable from one another).

[Table 1 about here]

Statistical analysis

Descriptive statistics (mean ± SD) were generated for all dependent variables and their distributions checked for normality via Shapiro-Wilk tests utilising SPSS (version 23, Chicago, USA). As these conditions were met, a one-way repeated measures analysis of variance (ANOVA) was used to compare mean values across punch types with Bonferroni-adjusted *t*-tests adopted as a post-hoc procedure to identify where specific differences existed. Effect sizes were calculated as: $d = (\bar{x}1-\bar{x}2) / SD$; where $\bar{x}1$ and $\bar{x}2$ represent the two sample means and SD the pooled standard deviation. The magnitude of Cohen's *d* effect sizes were classified as: trivial <0.2, small 0.2-0.6, moderate 0.6–1.2, large 1.2–2.0, and very large >2.0 (Hopkins, 2004). Furthermore, the relationships between kinematic and GRF (lead and rear leg), impulse (lead and rear leg net propulsive and vertical), and peak resultant fist velocity were assessed via the Pearson product-moment coefficient and interpreted with the thresholds: <0.1 (trivial); 0.1 – 0.3 (small); 0.3 – 0.5 (moderate); 0.5 – 0.7 (large); 0.7 – 0.9 (very large) and >0.9 (nearly perfect) (Hopkins, 2002).

Results

Fist velocity and punch delivery time

The effect of punch type on peak resultant fist velocity was significant ($F_{(2.1,\ 29.8)}$ = 35.1, P < 0.001), with the highest (lead hook) exhibiting a value twice that of the lowest (jab). Post-hoc analysis (Table 2a) confirmed this difference and that between the jab and all the other punch types to be significant (P = 0.001-0.018, ES = 1.1–1.8).

A significant punch type effect was noted for delivery time ($F_{(2.3,\ 41.4)}$ = 20.2, P < 0.001), principally on account of the jab's markedly shorter mean time than all other punch types (P < 0.001, ES = 1.2-1.3), except for the rear-hand cross (P = 0.034, ES = 0.6 - see Table 2a). The lead hook took the longest to deliver, being 62% and 33% greater than the jab (ES = 1.3) and rear-hand cross (ES = 1.0), respectively.

[Tables 2a & 2b about here]

Shoulder joint and elbow joint angular velocity

Punch type had a significant effect on mean peak shoulder joint resultant angular velocity ($F_{(2.2,\ 31.1)}$ = 32.7, P < 0.001), with significantly higher values evident in the two uppercuts compared to the other punches (P = 0.001-0.046, ES = 1.0–1.7), apart from the rear hook (P = 0.441-1.0, ES = 0.3–0.7). The jab and rear-hand cross had the lowest peak resultant velocities of the six punch types at the shoulder joint (see Table 2a). The timing of peak shoulder joint angular velocity occurred earliest in the jab (87 ± 7% of the movement), and latest in the rear hook (97 ± 2%).

Mean elbow peak angular velocities were consistently lower than observed at the shoulder, but interestingly, there was no overall difference in mean values among the punch types ($F_{(2.4, 32.9)} = 1.9$, $P = 0.167$). However, the highest value was again produced by one of the uppercuts (lead), and the lowest by the rear-hand cross. Lead and rear uppercuts achieved peak elbow joint angular velocity earlier than all other punch types, while the jab and rear-hand cross exhibited the latest peaks (see Table 2a)

The jab and rear hand cross exhibited a proximal-to-distal sequence for the shoulder and elbow joints, respectively, with the shoulder reaching peak angular joint velocity approximately 12 % (jab) and 8.5 % (rear-hand cross) before the elbow (Figure 5). Meanwhile, hooks and uppercuts did not exhibit upper-limb proximal-to-distal sequencing as peak angular elbow joint velocity occurred before that of the shoulder joint across all hook and uppercut punch types (Figures 6 and 7).

[Figures 5-7 about here]

Ground Reaction Force (GRF)

Peak resultant lead leg GRF was significantly different according to punch type ($F_{(3.6, 50.8)} = 32.5$, $P < 0.001$), being largest in the lead and rear uppercut punches and smallest in the jab (see Table 2b). Post-hoc analysis revealed the mean jab value to be significantly lower than all the other punches ($P < 0.001$, ES = 1.2–1.6). Punch type was also influenced for peak resultant rear leg GRF ($F_{(3.0,\ 42.3)} = 14.2$, $P < 0.001$), with the jab producing the greatest value (see Figure 8), being significantly higher than all other punch types (P = 0.001-0.004, ES = 0.8–1.4), except for the rear uppercut (P = 0.037, ES = 0.8). Differences of approximately 100 N were apparent between the two hook punches (lead and rear, ES = 0.6) and between the two uppercuts (lead and rear, ES = 0.4), but neither were significant. The comparison of peak lead and rear leg resultant GRF across punch types was significant for the jab punch only ($t_{(14)} = -11.7$, $P < 0.001$, ES = 1.6). Furthermore, peak vertical GRF accounted for a larger degree of the total peak GRF than anteroposterior or mediolateral GRF for both lead and rear legs across all punch types (see Figure 8).

[Figure 8 about here]

The effect of punch type on lead leg net braking impulse was significant ($F_{(2.44,\ 34.1)} = 13.9$, $P < 0.001$), with the highest (rear hook) exhibiting a value more than eight times that of the lowest (jab) (ES = 1.6). Post-hoc analysis (Table 2b) confirmed this difference to be significant, as were the differences between the jab and rear-hand cross, and lead uppercut ($P < 0.001$, ES = 1.5–1.6). Differences between the lead hook and rear hook were also significant (P < 0.001, ES = 1.3). Additionally, punch type had a significant effect on lead leg vertical impulse ($F_{(3.3,\ 46.8)} = 26.4$, $P < 0.001$), with the jab and rear-hand cross (which had the lowest lead leg vertical impulse values), significantly different to the lead hook and both uppercuts (P = 0.001-0.002, ES = 1.2–1.6), but not each other.

A significant punch type effect was noted for rear leg net propulsive impulse ($F_{(2.8, 39.7)}$ = 9.8, P < 0.001), primarily resulting from the notably lower impulse value exhibited by the lead hook compared to the rear-hand cross, rear hook, and lead uppercut (P = 0.001-0.002, ES = 1.0-1.4) (see Table 2b). No significant differences were observed for rear leg vertical impulse according to punch type ($F_{(3.1, 43.0)}$ = 1.5, P = 0.099), with four of the six punch types exhibiting comparable values (see Table 2b). Post-hoc analysis revealed the largest difference was between the jab and lead hook, but this was not significant (P = 0.35, ES = 0.6).

Relationship between peak resultant fist velocity and GRF, impulse, and kinematic, variables

Peak lead leg resultant GRF correlated with peak resultant fist velocity (r = 0.56) and peak shoulder joint resultant angular velocity (r = 0.55) of the lead hook (Table 3). Furthermore, peak elbow joint resultant angular velocity was strongly associated with jab (r = 0.78) and lead hook peak (r = 0.57) fist velocities, respectively. All other associations were generally weak and non-significant.

[Table 3 about here]

Discussion

Kinematic variables

The superior peak fist velocities of hook punches over straights and uppercuts corroborate the findings of Piorkowski at al. (2011) who also noted lead and rear hook generated greater fist velocities than the jab and rear-hand cross, respectively.

This can be explained by the greater range of motion available at the shoulder joint in comparison to the elbow (Whiting et al., 1988; Piorkowski et al., 2011; Loturco et al., 2016) and that hook punches also have a longer trajectory and subsequent acceleration pathway, facilitating the generation of greater end-point fist velocities than straight punches (Piorkowski, 2009). In contrast to Piorkowski et al. (2011), the lead hook, and not the rear hook, exhibited the greatest peak resultant fist velocity of all punch types. 2011). This conflict is likely a consequence of the computer-based scoring system used in 2011. That is, a high frequency of jab punches alongside an 'effective' rear hand punch, particularly the rear hook (Davis et al., 2013; 2015) was favoured for points scoring. Accordingly, the boxers assessed in Piorkowski et al. (2011) probably possessed greater technical competency for the rear hook than those in the present study. Under the current scoring system ('10-point must'), boxers execute lead hook punches more frequently (Davis et al., 2017; Thomson & Lamb, 2016), and likely possess an improved aptitude for this technique.

A notable finding was that of the rear uppercut generating greater peak fist velocities than both the rear-hand cross and rear hook. Such punches are deemed to be the hardest to master in boxing (Kapo et al., 2008), and are the most infrequent punch type observed in competition (Davis et al., 2017) owing to the close proximity between boxers and their counter-attacking nature (Hristovski, Davids, Araújo & Button, 2006; Thomson & Lamb, 2016). Cabral et al. (2010) suggested that the high fist velocities generated by the rear uppercut occur as a result of a forceful proximal-to-distal sequence. Whilst such sequencing also plays a role in straight (Cheraghi et al., 2014) and hook (Piorkowski et al., 2011) punches, the position of the punching arm relative to the centre of mass during a rear uppercut is likely optimal for generating muscular torque at the shoulder joint (Cabral et al., 2010).

The shortest delivery times across all punch types were observed in the straight punches owing to their linear trajectory from the ‘guard’ position and travelling the least distance to the target (Piorkowski et al., 2011). As expected, the jab possessed the lowest delivery time, which would explain why it is the most frequently executed punch within competition (Davis et al., 2013; Davis et al., 2015; Davis et al., 2017; Kapo et al., 2008; Thomson & Lamb, 2016). As a consequence, it can be employed in various ways; to judge and/or maintain the distance between opponents (limiting their counter-attacking opportunities), facilitate a positive impression among judges and create opportunities to land more forceful punches (such as the rear-hand cross or lead hook) (Haislet, 1968; Markovic, Suzovic, Kasum & Jaric, 2016), and provide an opponent with less time to defend/evade it, increasing its likelihood of landing cleanly (Piorkowski et al., 2011).

That hook and uppercut delivery times were not significantly different for both lead and rear hand variations was interesting, given that, regardless of ability level, the uppercut is the least frequently used punch in competition (Davis et al., 2017; El Ashker, 2011; Thomson & Lamb, 2016). Therefore, as uppercuts possess similar delivery time to hooks and can cause considerable ‘damage’ to an opponent resulting from their vertical trajectory (i.e. travel underneath an opponent’s line of vision), unpredictability (due to their limited use in competition), and large impact forces (Arus, 2013; Cabral et al., 2010; Slimani et al., 2017; Thomson & Lamb, 2016; Viano et al., 2005), coaches and boxers should take heed of this finding and consider an increased application of uppercuts in training and competition.

Perhaps unsurprisingly given the above observation, both types of uppercut exhibited the greatest peak values for shoulder-joint angular velocity, with the lead uppercut also generating the highest peak elbow-joint angular velocity values of all punch types. As the kinematics of the lead uppercut have not been described previously, this is a novel finding.

However, with regards to the moments of peak shoulder and elbow joint angular velocities, only straight punches (jab and rear-hand cross) exhibited a proximal-to-distal sequence of the upper limbs. This is in agreement with previous studies that have reported how shoulder angular velocity peaks prior to the elbow during the rear-hand cross (Cheraghi et al., 2014; Turner et al., 2011). That such a sequence was evident for the jab also has not been observed before. It is suggested that hooks and uppercuts failed to exhibit a proximal-to-distal sequence due to the 'fixed' elbow positions associated with these punch types. Indeed, during straight punches, the elbow joint rapidly extends after the punching arm has already started accelerating towards the target via angular velocities generated at the shoulder joint (Cheraghi et al., 2014; Jessop & Pain, 2016). However, during hooks and uppercuts, the elbow is flexed to 'fixed' ~90° angle whilst the shoulder exhibits a rapid combination of abduction followed by flexion, protraction, and adduction from INITIATION to CONTACT, which may explain why peak angular velocities at the shoulder joint were markedly higher than those at the elbow across hooks and uppercuts. Consequently, it appears that peak elbow joint angular velocity occurs prior to the elbow's ~90° position during hooks and uppercuts, and may assist in generating additional kinetic energy that, in conjunction with the angular velocities generated at the shoulder, accelerate the fist rapidly towards the target.

The peaks and timing of peak angular joint velocities for the shoulder and elbow, respectively, provide noteworthy information regarding the role of each joint across different punches and the degree to which they contribute to the end product of a punch (fist velocity and delivery time). This data provides useful information for coaches and boxers that may assist in the development of resistance training strategies. More specifically, resistance training strategies designed to augment angular velocities generated at the shoulder and elbow across various punch-specific positions (e.g. shoulder abducted to 90° relative to the torso for lead and rear hooks), and subsequently, the 'damage' potential of specific punch types.

Kinetic (GRF and impulse) variables

Based on previous studies which have highlighted the importance of the lead leg to lead hand punches and the rear leg to rear hand punches (Cheraghi et al., 2014; Turner et al, 2011; Yan-ju et al., 2013), it was expected that the lead leg would produce greater GRF during lead hand punches, and likewise rear leg for rear hand punches. However, the current findings revealed that uppercuts (lead and rear) generated the greatest peak resultant GRF values for the lead leg across punch types (see Table 1). Moreover, it was interesting to find that both uppercuts produced greater peak lead leg resultant GRF values than straight and hook punches. In the absence of related research to assist interpretation for this finding, it is suggested that force orientation is a contributory factor in such movements (Bahamonde & Knudson, 2001; Morin, Edouard & Samozino, 2011; Plessa, Rousanoglou & Boudolos, 2010). That is, uppercuts (lead and rear) may generate the greatest peak lead leg resultant GRF owing to the larger peak lead leg vertical GRF values recorded for these punch types (in comparison to straights and hooks), alongside the predominantly vertical trajectory of the fist and a potential symbiotic relationship between these two characteristics.

That the rear uppercut generated higher peak lead leg resultant GRF than the jab and lead hook, respectively, was unexpected, as was the lead hook producing the greatest vertical impulse, while the rear hook generated the largest net braking impulse. It is possible that these findings relate to the influence of the lead leg in producing a stable base from which to generate force proximally to the distal segments (i.e. the fist) (Cabral et al., 2010). Such a role has been reported for other activities requiring movements with lower-body kinematics similar to those of rear hand punches (i.e. triple extension of the hip, knee and ankle; trunk rotation; rapid projection of the arm). For example, Bartonietz (1994) noted that the lead leg produced forces up to three times that of the rear leg in shot putting (no values though reported), while McCoy et al. (1984) determined ~95% of 'shot velocity' (i.e. velocity of the shot put when released from the hand) was influenced by vertical braking forces produced by the lead leg. Furthermore, the majority of lead leg GRF and impulse was concentrated in a vertical direction (see Table 1 and Figure 11), which is similar to findings observed in the above activities and baseball pitching (MacWilliams, Choi, Perezous, Chao & MacFarland, 1998). The considerable vertical GRF, net braking, and vertical impulse result from the extensive braking demands (rapid eccentric muscular contractions to prevent excessive knee flexion) that assist in facilitating the propulsive vertical forces generated by the rear leg to travel superiorly to the distal segments of the body (i.e. fist/hand) (Williams, 2012). This corroborates previous boxing research which has highlighted that during the rear-hand cross punch, the ability of a boxer to maintain a rigid lead leg (through the production of vertical anterior-posterior braking forces (i.e. impulse)) during a punch has assists in the transmission of force from the lower limbs to the arm/hand segments via the kinetic chain (Cheraghi et al., 2014; Turner et al., 2011). The current findings implicate the rigidity and braking forces of the lead leg play a crucial role for both the lead and rear uppercut, and that they are more evident than for the rear-hand cross.

The observed higher GRF values of the rear leg, rear-hand cross, rear hook and rear uppercut techniques than the lead hook and lead uppercut, confirm the importance of the rear leg to rear hand punches noted previously (Cheraghi et al., 2014; Filimonov et al., 1985; Gulledge & Dapena, 2008; Turner et al. 2011). However, that the rear leg produced ~71% of the total GRF during the jab - greater than for any other punch type - was a novel finding. It is plausible to suggest that rear leg resultant GRF is less reliant on trunk rotation and upper-body stretch-shortening cycle characteristics, and instead, requires a high degree of rear leg resultant GRF to propel the fist rapidly along the anterior-posterior axis towards the opponent/target. Moreover, as the lead hook generated the largest vertical impulse and the rear hook the largest net propulsive impulse for the rear leg, it appears that these two punches produced the highest forces over the duration of each punch from INITIATION to CONTACT.

Previous research has reported the importance of impulse to explosive dynamic movements (Davies, Orr, Halaki & Hackett, 2016; Suchomel & Sole, 2017), and, more specifically, that enhancing the braking (antero-posterior and vertical) impulse of the lead leg may increase the force of a punch owing to an increase in velocity, and subsequently momentum (mass x velocity) (Turner et al., 2011). Indeed, it is suggested that the greater the vertical and net propulsive impulse produced by the rear leg, the greater the overall momentum and peak fist velocities generated. Consequently, it seems reasonable to suggest that the more GRF a boxer can produce from the initiation of a punch to the point of impact with the target, the larger the degree of energy generated by the kinetic chain. In turn, this yields greater resultant joint angular velocities generated by the upper-limbs (shoulder and elbow) and linear velocity of the fist towards the target. Future research should investigate the role of impulse to maximal punching, its relationship to GRF during maximal punching, and assess whether enhancing this kinetic variable can improve the characteristics of maximal punching performance.

Relationships between kinematic and kinetic variables

As expected, lead hook peak resultant fist velocity exhibited a significant (moderate) relationship with peak lead leg resultant GRF, signifying the influence of the vertical GRF produced by the lead leg. On this evidence, it is proposed that as part of training/technical practice, boxers aiming to increase the velocity of the fist and the damage-causing capabilities of this punch attempt to focus deliberately on generating force through the lead leg during the initiation and delivery of the lead hook. In addition, as previous research has highlighted the importance of lower-body strength to maximal punching (Loturco et al., 2014, 2016; Stanley, 2014; Zekas, 2016), coaches and boxers should consider the implementation of axial-loaded lower-body resistance exercises (e.g. squats, deadlifts, cleans, lunges) that emphasise triple extension (hip, knee and ankle) force production (Lenetsky et al., 2013; Turner et al., 2011), alongside traditional skill-based practice in order to enhance the peak vertical and resultant GRF potential of the lead leg.

Peak shoulder joint angular velocity also exhibited a moderate relationship with peak lead hook fist velocity, confirming the findings of Piorkowski (2009. It has been suggested that rear-hand crosses (Karpilowski, Nosarzewski, Staniak &

Trzaskoma, 2001), lead and rear hooks (Piorkowski et al., 2011; Whiting et al., 1988), and lead and rear uppercuts (Cabral et al., 2010) produce a stretch-reflex (via the SSC) at the shoulder joint which potentiates the ensuing concentric muscular contraction, and subsequently, fist velocity. Therefore, it would appear that resistance training exercises that improve a boxer's ability to rapidly abduct and adduct the punching arm may enhance the end-point velocity of the fist, and subsequently, its damage-causing potential. Furthermore, as the upper-body kinematics of punching comprise a multitude of joint motions, including shoulder adduction, abduction, flexion and extension (Cabral et al., 2010; Piorkowski et al., 2011), a boxer's training regimen should aim to incorporate ballistic resistance exercises that enhance speed and velocity characteristics of the musculature (deltoid, pectoralis major and minor, latissimus dorsi, and serratus anterior) that facilitate such motions, alongside regular technical practice (Piorkowski et al., 2011; Turner et al., 2011; Veegera & Van Der Helma, 2007).

The significant association between peak elbow angular velocity and lead hook peak resultant fist velocity has not been documented in previous research, and it is suggested that, in a similar manner to the shoulder joint, the elbow joint exhibits a stretch-reflex following INITIATION that facilitates the generation of large peak fist velocities. Indeed, at the onset of INITIATION, the elbow may extend slightly from its flexed ~90° angle as the shoulder abducts before rapidly adducting as the fist is projected towards the target. Although further research is required to establish if kinetic and kinematic variables associated with maximal punching performance are optimised if the elbow joint is extended and flexed rapidly or fixed at a ~90° angle, enhancing the eccentric strength and SSC efficiency of the musculature surrounding the elbow joint would appear to increase stability and force production potential of the lead hook (Cormie, McGuigan & Newton, 2011; Zatsiorsky & Kraemer, 2006).

Given the findings of Piorkowski et al. (2011) it was unsurprising to observe the link between peak jab resultant fist velocity and elbow joint angular. This likely occurs as a consequence of the jab often being less reliant upon SSC characteristics at the shoulder joint and trunk in order to minimise its delivery time, and therefore enhance its likelihood of striking the opponent before they can defend/evade (Haislet, 1968; Hickey, 2006). It would appear that enhancing a boxer's ability to extend the punching arm as rapidly and forcibly as possible (elbow extension) may increase peak jab fist velocity, and consequently, could improve competitive performance considering the jab to the head of an opponent is the most frequently executed punch within competitive bouts (Davis et al., 2015; Davis et al., 2017; Thomson & Lamb, 2016). Moreover, increasing the rate of force development (RFD) of the elbow extensors (via elastic resistance training) has been shown to improve peak jab velocity as much as 11% ($P < 0.01$) in competitive boxers, (Markovic, Suzovic, Kasum & Jaric, 2016). Therefore, it is recommended that boxers include resistance exercises in their training programme that increase the strength of the tricep brachii musculature (primary muscle group responsible for elbow extension) to improve elbow joint velocity, and subsequently, peak jab fist velocity.

Limitations

Though the current study provides a comprehensive analysis of the biomechanical characteristics associated with maximal punching, there are two limitations to acknowledge. Firstly, the experience and sub-elite ability level of the boxers in the present study suggests the findings herein might not generalise to higher standards of boxing. Therefore, future research should assess the punching performance of a more heterogeneous sample to identify key kinetic and kinematic differences that might exist according to ability and experience levels.

Secondly, the position of the force plates relative to the punch target necessitated that the taller boxers in the sample (≥ 1.8 m; $n = 6$) made contact with the target before reaching full elbow extension during straight punches. As self-selected punching distances have been shown to produce superior ($P < 0.05$) punch kinetics values than fixed distances (Loturco et al., 2014; Loturco et al., 2016; Neto et al., 2012), future research should seek to analyse the kinetics and kinematics of maximal punching whereby boxers are permitted to punch from a self-selected distance relative to the target.

Conclusion

In appraising the kinetic and kinematic characteristics of six traditional punch techniques implemented within amateur boxing, the present study has revealed that: (i) the lead hook produced the greatest peak resultant fist velocity values; (ii) the jab recorded the shortest delivery time; (iii) peak lead and rear leg resultant GRF were comparable across all punch types except for the jab, with force primarily applied in a vertical direction; (iv) punch-specific inter-relationships exist between peak fist and joint angular velocities, and peak fist velocities and GRF. Whilst alone these findings advance our biomechanical understanding of maximal punching, there is now scope to investigate the links between boxers' physical qualities and the key kinetic and kinematic variables, leading potentially to the development of punch-specific strength and conditioning strategies.

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An analysis of the three-dimensional kinetics and kinematics of maximal effort punches among amateur boxers

Abstract

The purpose of this study was to quantify the 3D kinetics and kinematics of six punch types among amateur boxers. Fifteen males (age: 24.9 ± 4.2 years; stature: 1.78 ± 0.1 m; body mass: 75.3 ± 13.4 kg; boxing experience: 6.3 ± 2.8 y) performed maximal effort punches against a suspended punch bag during which upper-body kinematics were assessed via a 3D motion capture system, and ground reaction forces (GRF) of the lead and rear legs via two force plates. For all variables except elbow joint angular velocity, analysis revealed significant ($P < 0.05$) differences between straight, hook and uppercut punches. The lead hook exhibited the greatest peak fist velocity (11.95 ± 1.84 m/s), the jab the shortest delivery time (405 ± 0.15 ms), the rear uppercut the greatest shoulder joint angular velocity (1069.8 ± 104.5 deg/s), and the lead uppercut the greatest elbow angular velocity (651.0 ± 357.5 deg/s). Peak resultant GRF differed significantly ($P < 0.05$) between rear and lead legs for the jab punch only. Whilst these findings provide novel descriptive data for coaches and boxers, future research should examine if physical and physiological capabilities relate to the key biomechanical qualities associated with maximal punching performance.

Key words: combat sports, boxing, punching, technique analysis.

Introduction

Boxing punches are intricate actions requiring the recruitment of leg, trunk and arm musculature to function synergistically in a coordinated manner (Turner, Baker & Miller, 2011). Despite the importance of punching to successful performance, there is only a limited amount of biomechanical knowledge for most of its techniques. Some kinematic characteristics (such as joint angles and velocities and punch velocity) have been investigated for certain punches (jabs, rear-hand crosses, lead hooks, rear hooks and rear uppercuts: Cabral et al., 2010; Cheraghi et al., 2014: Kimm & Thiel, 2015; Piorkowski et al., 2011) among competitive boxers. For example, research has reported the delivery times and fist velocities of straight (357 ± 178 ms and 5.9 m/s – 8.22 m/s) and hook (477 ± 203 ms and 8 m/s – 11 m/s) punches, respectively (Cheraghi et al., 2014; Kimm & Thiel, 2015; Piorkowski et al., 2011; Whiting et al., 1988).

Joint and punch velocities are dependent upon a proximal-to-distal sequencing pattern initiated by the lower limbs that travels distally through the pelvis, trunk and arm before peaking at the fist, causing the acceleration of the fist towards the target (Cheraghi et al., 2014). Proximal-to-distal sequencing and the subsequent velocities generated via rapid joint rotations have been observed in various punching and kicking techniques across combat sports (Estevan, Falco, Silvernail & Jandacka, 2015; Sorensen, Zacho, Simonsen, Dyhre-Poulsen & Klausen, 1996; VencesBrito, Rodrigues Ferreira, Cortes, Fernandes & Pezarat-Correia, 2011). Fist velocity has also been suggested to be dependent upon the distance of the acceleration path to the target, with hook punches exhibiting greater values than straight punches due to a longer acceleration pathway that facilitates the generation of greater pre-impact fist velocities (Piorkowski et al., 2011; Viano et al., 2005; Whiting et al., 1988). However, how joint and fist velocity differ between straight, hooks and uppercuts has not been reported within the scientific literature.

Kinetic characteristics have also been shown to influence properties of punching, particularly ground reaction forces (GRF) (Mack, Stojsih, Sherman, Dau & Bir, 2010; Yan-ju, Yi-gang, Yan & Zheng-Ping, 2013). For example, the force generated by the rear leg has been suggested to contribute considerably to the performance of rear hand punches (Cheraghi et al., 2014; Filimonov et al., 1985; Turner et al., 2011), whilst Yan-ju et al. (2013) noted that lead leg force was a significant contributor to jab fist velocity. However, Mack et al. (2010) reported small, albeit significant, relationships between lower body forces and peak hand velocity for rear hook (R^2 = 0.103) and rear-hand cross (R^2 = 0.099) punches, respectively, suggesting that further research is warranted here. Moreover, whilst their relevance has been alluded to (Lenetsky et al, 2013), no scientific studies have examined the directional (anteroposterior, mediolateral, vertical) application of GRF during specific punch types.

With the general lack of empirical evidence, coaches and boxers are unlikely to have the means to form an understanding of how punches can be enhanced through kinetic and kinematic assessments and how knowledge and information quantified via such assessments can influence performance. In the manner of previous appraisals of sports techniques (Kageyama, Sugiyama, Takai, Kanehisa & Maeda, 2014; Torres, 2013; Wagner et al., 2014), gathering information relating to fist velocity, GRF production and their relationship across different punch techniques could facilitate a grasp of the technical intricacies of different punch techniques and lead to the development of punch-specific training interventions.

The overall aim of this study therefore was to quantify the GRF and kinematic characteristics of a variety of maximal punches among amateur boxers. The main objectives were to: (i) assess peak fist velocities and delivery times across punch types; (ii) examine the differences in lead and rear leg resultant GRF and its directional application across punch types; (iii) quantify lead leg net braking, rear leg net propulsive and lead and rear leg vertical impulse across punch types, and (iv) quantify the relationships between kinematic (punch delivery time, peak shoulder joint resultant angular velocity, peak elbow joint resultant angular velocity) and kinetic (peak lead and rear leg resultant GRF, lead leg net braking and vertical impulse, rear leg net propulsive and vertical impulse) variables and peak resultant fist velocity.

Methods

Participants

Fifteen males (age: 24.9 ± 4.2 years; stature: 1.78 ± 0.1 m; body mass: 75.3 ± 13.4 kg; years of experience: 6.3 ± 2.8 years) across seven weight categories (flyweight to super-heavyweight) were recruited from six amateur boxing clubs located across the North West of England, based upon current boxing experience (≥ 2 years) and official bout history (≥ 2 bouts). A sample size calculation (G*Power version 3.1.9, Universität Düsseldorf, Dusseldorf, Germany - Faul et al., 2009) based on standard input parameters (α level = 0.05, power = 0.8) and effect sizes (0.68 for punch delivery time and 0.99 for contact speed) gleaned from Piorkowski et al. (2011), yielded a sample of 12. All participants provided written informed consent prior to the study and institutional ethical approval was granted by the Faculty of Medicine, Dentistry and Life Sciences Research Ethics Committee.

Design

The study adopted a within-subjects design to assess kinetic and kinematic aspects of straight, hook and uppercut punches, considered to represent the principal techniques observed in boxing competition (El Ashker, 2011; Kapo et al., 2008; Thomson & Lamb, 2016). All data were collected in one session and participants did not require a separate familiarisation trial as all had experience (≥ 2 years) performing the punch techniques and were familiar with punching a target similar to that used in the present study. Four kinematic and six kinetic variables were measured with respect to the six punch types via a 3D motion capture system and two embedded force platforms, respectively.

Procedures

For all punch trials, a water-filled punch bag that resembled the average height of a human head (9 in) (Aqua Bag 'Headhunter' model, Aqua Training Bag, New York, United States) was used to provide a striking target (see Figure 1). Utilising a punch target that moves upon impact has been advocated (Atha et al., 1985; Nakano, Lino, Imura & Kojima, 2014) as an effective way of ensuring maximal effort punches. The punch bag was suspended at the shoulder level of each participant by a heavy duty steel chain secured by a punch bag hook located above the designated testing area. Three reflective markers were placed on the top of the punch bag in order to permit the 3D cameras to detect its movement upon impact. This movement acted to verify the instance of punch contact (see Figure 2).

[Figures 1 & 2 about here]

Seventy six reflective markers were placed on specific anatomical landmarks of each participant to facilitate a comprehensive assessment of full-body kinematics in 3D spaces across six degrees of freedom (see Figure 3). Of the 76 markers, 18 were utilised for calibration purposes only and were removed during the dynamic trials. With the exception of the head (not required for analysis) and the addition of hand segments (Figure 3) in the manner of Piorkowski et al. (2011) (to obtain detailed fist velocity data), the defined body segments for all punch trials corresponded with those used by Vanrenterghem, Gormley, Robinson and Lees (2010). These segments included the upper arm (left and right), lower arm (left and right), thorax, pelvis, upper leg (left and right), lower leg (left and right), and foot (left and right). Markers allocated to the ‘radial wrist’, ‘ulnar wrist’ and ‘glove centre’ defined the hand segment (see Figure 4).

[Figures 3 & 4 about here]

The 3D positions of all reflective markers were obtained from eight infrared, opto-electric ceiling mounted cameras (Oqus 7+ system, Qualisys Inc., Gothenburg, Sweden). Kinematic data was obtained via Qualisys Track Manager (QTM) (Version

2.14, Qualisys Inc., Gothenburg, Sweden) and subsequently analysed using Visual 3D (Version 6, C-Motion Inc., Rockville, United States). All marker data were filtered using a low-pass Butterworth filter with a cut-off frequency of 12 Hz prior to and after the computer link-model based data had been generated to reduce the potential noise in the signal, as suggested in previous boxing-related research (Piorkowski et al., 2011). This cut-off frequency was deemed appropriate following pilot work whereby discrepancies in data were visually inspected for unwanted signal noise. The same data processing methods were implemented across the data-set, meaning any potential errors were consistent.

GRF data were collected from both the lead and rear legs of each participant for all punch trials by two embedded force platforms (model 9281CA with 600 x 400 mm internal amplifiers, Kistler Instruments, Hampshire, UK). GRF data were low-pass filtered using a 4th-order Butterworth filter with a cut-off frequency of 100 Hz based on the recommendations of Bezodis, Salo and Trewartha (2011).

Prior to testing, participants completed a 10 min self-selected warm-up comprising generic and boxing-specific activities such as jogging, dynamic stretches and shadow-boxing (Smith et al., 2000). The boxers were permitted to strike the punch bag whilst wearing the reflective markers until they became familiarised with the set up and positioning of the target (~5 min). All were instructed to strike the punch bag using a single, maximum effort punch (termed as a ‘knock-out’ punch) whilst maintaining the correct technique for the specific punch type performed. Boxers wore fabric hand-wraps (450 cm length, 5 cm width; Adidas, Germany) and boxing gloves (284 g; Adidas, Germany) as required during competition.

Six punch types (jab, rear-hand cross, lead hook, rear hook, lead uppercut, rear uppercut) were performed from either an orthodox (left foot leading) or southpaw (right foot leading) stance (Hickey, 2006), depending on the preference of each participant (orthodox n = 11; southpaw n = 4). Each punch was performed five times in succession with 60 s recovery period between trials. In the manner of previous related research (Lenetsky, Brughelli, Nates, Cross, & Lormier, 2017), all punches were performed in groups per each punch types in the order of (1) jab; (2) rear-hand cross; (3) lead hook; (4) rear hook; (5) lead uppercut and; (6) rear uppercut. Performance feedback was not provided during the testing procedures.

Data processing

Kinematic and GRF data was analysed via Qualisys Track Manager (QTM) (version 2.14, Qualisys Inc., Gothenburg, Sweden), whereby reflective markers and anatomical landmarks were labelled. Thereafter, punch trials were exported to Visual 3D (Version 6, C-Motion Inc., Rockville, United States) from which full-body joint segments and key events were created alongside the calculation of kinematic and GRF data. Key events (see below) were identified from visual observations due to the differing technical intricacies and punch set-ups across each individual participant (e.g. a hook punch performed directly from the guard versus a hook punch thrown from a 'bobbing and weaving' motion). These events were classified as: (i) INITIATION (the initiation of a countermovement prior to the fist being projected towards the punch target), identified from the descent of the hand segment markers on the punching hand along the longitudinal axis; and (ii) CONTACT (one frame prior to the fist impacting the punch target), identified from the initial movement of the markers located on the punch target. These event labels were subsequently used to export kinematic and GRF data in ASCII formats to be further analysed in Microsoft Excel (Microsoft Corporation, Reading, UK).

The kinematic variables computed from the punch data were: punch delivery time from event markers INITIATION to CONTACT, peak resultant fist velocity of the hand segment (defined from 'radial wrist', 'ulnar wrist', 'knuckle 1', and 'knuckle 5' tracking markers) from INITIATION to CONTACT, peak resultant shoulder joint angular vector velocity (shoulder joint defined from upper arm tracking markers relative to the defined thorax/ab segment) from INITIATION to CONTACT, and peak resultant elbow joint angular vector velocity (elbow joint defined from the upper arm and forearm tracking markers) from INITIATION to CONTACT. Peak joint velocity timings were quantified from the moment of peak angular joint velocity (shoulder and elbow) from punch data normalised to 101 data points.

The kinetic variables computed from the punch data were: peak lead leg resultant GRF, peak rear leg resultant GRF, total lead leg net braking impulse, lead leg vertical impulse, total rear leg net propulsive impulse, and total rear leg vertical impulse (all from INITIATION to CONTACT). All GRF data (peaks and impulses) were normalised to participants' body mass (N/kg).

INITIATION key event identification

The instant of INITIATION for each punch type was subject to test-retest intra-observer reliability testing. For each punch type, ten trials were randomly selected for analysis with the time between force plate contact (recorded objectively by the Kistler platforms) and punch initiation (determined by the lead researcher) recorded in

Visual 3D. Analysis revealed INITIATION identification was consistent across punch trials, with low typical error (Hopkins, 2000), low CV% (Roberts & Priest, 2006), and narrow limits of agreement (Bland & Altman, 1999) observed for each punch type (see Table 1). Consequently, the reliability of punch INITIATION was deemed acceptable given the variation was unlikely to have had a meaningful impact upon the interpretation of the dependent variables (i.e. punches remained distinguishable from one another).

[Table 1 about here]

Statistical analysis

Descriptive statistics (mean ± SD) were generated for all dependent variables and their distributions checked for normality via Shapiro-Wilk tests utilising SPSS (version 23, Chicago, USA). As these conditions were met, a one-way repeated measures analysis of variance (ANOVA) was used to compare mean values across punch types with Bonferroni-adjusted *t*-tests adopted as a post-hoc procedure to identify where specific differences existed. Effect sizes were calculated as: $d = (\bar{x}1-\bar{x}2) / SD$; where $\bar{x}1$ and $\bar{x}2$ represent the two sample means and SD the pooled standard deviation. The magnitude of Cohen's *d* effect sizes were classified as: trivial <0.2, small 0.2-0.6, moderate 0.6–1.2, large 1.2–2.0, and very large >2.0 (Hopkins, 2004). Furthermore, the relationships between kinematic and GRF (lead and rear leg), impulse (lead and rear leg net propulsive and vertical), and peak resultant fist velocity were assessed via the Pearson product-moment coefficient and interpreted with the thresholds: <0.1 (trivial); 0.1 – 0.3 (small); 0.3 – 0.5 (moderate); 0.5 – 0.7 (large); 0.7 – 0.9 (very large) and >0.9 (nearly perfect) (Hopkins, 2002).

Results

Fist velocity and punch delivery time

The effect of punch type on peak resultant fist velocity was significant ($F_{(2.1,\ 29.8)}$ = 35.1, P < 0.001), with the highest (lead hook) exhibiting a value twice that of the lowest (jab). Post-hoc analysis (Table 2a) confirmed this difference and that between the jab and all the other punch types to be significant (P = 0.001-0.018, ES = 1.1–1.8).

A significant punch type effect was noted for delivery time ($F_{(2.3,\ 41.4)}$ = 20.2, P < 0.001), principally on account of the jab's markedly shorter mean time than all other punch types (P < 0.001, ES = 1.2-1.3), except for the rear-hand cross (P = 0.034, ES = 0.6 - see Table 2a). The lead hook took the longest to deliver, being 62% and 33% greater than the jab (ES = 1.3) and rear-hand cross (ES = 1.0), respectively.

[Tables 2a & 2b about here]

Shoulder joint and elbow joint angular velocity

Punch type had a significant effect on mean peak shoulder joint resultant angular velocity ($F_{(2.2,\ 31.1)}$ = 32.7, P < 0.001), with significantly higher values evident in the two uppercuts compared to the other punches (P = 0.001-0.046, ES = 1.0–1.7), apart from the rear hook (P = 0.441-1.0, ES = 0.3–0.7). The jab and rear-hand cross had the lowest peak resultant velocities of the six punch types at the shoulder joint (see Table 2a). The timing of peak shoulder joint angular velocity occurred earliest in the jab (87 ± 7% of the movement), and latest in the rear hook (97 ± 2%).

Mean elbow peak angular velocities were consistently lower than observed at the shoulder, but interestingly, there was no overall difference in mean values among the punch types ($F_{(2.4,\ 32.9)} = 1.9$, $P = 0.167$). However, the highest value was again produced by one of the uppercuts (lead), and the lowest by the rear-hand cross. Lead and rear uppercuts achieved peak elbow joint angular velocity earlier than all other punch types, while the jab and rear-hand cross exhibited the latest peaks (see Table 2a)

The jab and rear hand cross exhibited a proximal-to-distal sequence for the shoulder and elbow joints, respectively, with the shoulder reaching peak angular joint velocity approximately 12 % (jab) and 8.5 % (rear-hand cross) before the elbow (Figure 5). Meanwhile, hooks and uppercuts did not exhibit upper-limb proximal-to-distal sequencing as peak angular elbow joint velocity occurred before that of the shoulder joint across all hook and uppercut punch types (Figures 6 and 7).

[Figures 5-7 about here]

Ground Reaction Force (GRF)

Peak resultant lead leg GRF was significantly different according to punch type ($F_{(3.6,\ 50.8)} = 32.5$, $P < 0.001$), being largest in the lead and rear uppercut punches and smallest in the jab (see Table 2b). Post-hoc analysis revealed the mean jab value to be significantly lower than all the other punches ($P < 0.001$, ES = 1.2–1.6). Punch type was also influenced for peak resultant rear leg GRF ($F_{(3.0,\ 42.3)}$ = 14.2, P < 0.001), with the jab producing the greatest value (see Figure 8), being significantly higher than all other punch types (P = 0.001-0.004, ES = 0.8–1.4), except for the rear uppercut (P = 0.037, ES = 0.8). Differences of approximately 100 N were apparent between the two hook punches (lead and rear, ES = 0.6) and between the two uppercuts (lead and rear, ES = 0.4), but neither were significant. The comparison of peak lead and rear leg resultant GRF across punch types was significant for the jab punch only ($t_{(14)}$ = -11.7, P < 0.001, ES = 1.6). Furthermore, peak vertical GRF accounted for a larger degree of the total peak GRF than anteroposterior or mediolateral GRF for both lead and rear legs across all punch types (see Figure 8).

[Figure 8 about here]

The effect of punch type on lead leg net braking impulse was significant ($F_{(2.44,\ 34.1)}$ = 13.9, P < 0.001), with the highest (rear hook) exhibiting a value more than eight times that of the lowest (jab) (ES = 1.6). Post-hoc analysis (Table 2b) confirmed this difference to be significant, as were the differences between the jab and rear-hand cross, and lead uppercut (P < 0.001, ES = 1.5–1.6). Differences between the lead hook and rear hook were also significant (P < 0.001, ES = 1.3). Additionally, punch type had a significant effect on lead leg vertical impulse ($F_{(3.3,\ 46.8)}$ = 26.4, P < 0.001), with the jab and rear-hand cross (which had the lowest lead leg vertical impulse values), significantly different to the lead hook and both uppercuts (P = 0.001-0.002, ES = 1.2–1.6), but not each other.

A significant punch type effect was noted for rear leg net propulsive impulse ($F_{(2.8, 39.7)}$ = 9.8, P < 0.001), primarily resulting from the notably lower impulse value exhibited by the lead hook compared to the rear-hand cross, rear hook, and lead uppercut (P = 0.001-0.002, ES = 1.0-1.4) (see Table 2b). No significant differences were observed for rear leg vertical impulse according to punch type ($F_{(3.1, 43.0)}$ = 1.5, P = 0.099), with four of the six punch types exhibiting comparable values (see Table 2b). Post-hoc analysis revealed the largest difference was between the jab and lead hook, but this was not significant (P = 0.35, ES = 0.6).

Relationship between peak resultant fist velocity and GRF, impulse, and kinematic, variables

Peak lead leg resultant GRF correlated with peak resultant fist velocity (r = 0.56) and peak shoulder joint resultant angular velocity (r = 0.55) of the lead hook (Table 3). Furthermore, peak elbow joint resultant angular velocity was strongly associated with jab (r = 0.78) and lead hook peak (r = 0.57) fist velocities, respectively. All other associations were generally weak and non-significant.

[Table 3 about here]

Discussion

Kinematic variables

The superior peak fist velocities of hook punches over straights and uppercuts corroborate the findings of Piorkowski at al. (2011) who also noted lead and rear hook generated greater fist velocities than the jab and rear-hand cross, respectively.

This can be explained by the greater range of motion available at the shoulder joint in comparison to the elbow (Whiting et al., 1988; Piorkowski et al., 2011; Loturco et al., 2016) and that hook punches also have a longer trajectory and subsequent acceleration pathway, facilitating the generation of greater end-point fist velocities than straight punches (Piorkowski, 2009). In contrast to Piorkowski et al. (2011), the lead hook, and not the rear hook, exhibited the greatest peak resultant fist velocity of all punch types. 2011). This conflict is likely a consequence of the computer-based scoring system used in 2011. That is, a high frequency of jab punches alongside an ‘effective’ rear hand punch, particularly the rear hook (Davis et al., 2013; 2015) was favoured for points scoring. Accordingly, the boxers assessed in Piorkowski et al. (2011) probably possessed greater technical competency for the rear hook than those in the present study. Under the current scoring system (‘10-point must’), boxers execute lead hook punches more frequently (Davis et al., 2017; Thomson & Lamb, 2016), and likely possess an improved aptitude for this technique.

A notable finding was that of the rear uppercut generating greater peak fist velocities than both the rear-hand cross and rear hook. Such punches are deemed to be the hardest to master in boxing (Kapo et al., 2008), and are the most infrequent punch type observed in competition (Davis et al., 2017) owing to the close proximity between boxers and their counter-attacking nature (Hristovski, Davids, Araújo & Button, 2006; Thomson & Lamb, 2016). Cabral et al. (2010) suggested that the high fist velocities generated by the rear uppercut occur as a result of a forceful proximal-to-distal sequence. Whilst such sequencing also plays a role in straight (Cheraghi et al., 2014) and hook (Piorkowski et al., 2011) punches, the position of the punching arm relative to the centre of mass during a rear uppercut is likely optimal for generating muscular torque at the shoulder joint (Cabral et al., 2010).

The shortest delivery times across all punch types were observed in the straight punches owing to their linear trajectory from the 'guard' position and travelling the least distance to the target (Piorkowski et al., 2011). As expected, the jab possessed the lowest delivery time, which would explain why it is the most frequently executed punch within competition (Davis et al., 2013; Davis et al., 2015; Davis et al., 2017; Kapo et al., 2008; Thomson & Lamb, 2016). As a consequence, it can be employed in various ways; to judge and/or maintain the distance between opponents (limiting their counter-attacking opportunities), facilitate a positive impression among judges and create opportunities to land more forceful punches (such as the rear-hand cross or lead hook) (Haislet, 1968; Markovic, Suzovic, Kasum & Jaric, 2016), and provide an opponent with less time to defend/evade it, increasing its likelihood of landing cleanly (Piorkowski et al., 2011).

That hook and uppercut delivery times were not significantly different for both lead and rear hand variations was interesting, given that, regardless of ability level, the uppercut is the least frequently used punch in competition (Davis et al., 2017; El Ashker, 2011; Thomson & Lamb, 2016). Therefore, as uppercuts possess similar delivery time to hooks and can cause considerable 'damage' to an opponent resulting from their vertical trajectory (i.e. travel underneath an opponent's line of vision), unpredictability (due to their limited use in competition), and large impact forces (Arus, 2013; Cabral et al., 2010; Slimani et al., 2017; Thomson & Lamb, 2016; Viano et al., 2005), coaches and boxers should take heed of this finding and consider an increased application of uppercuts in training and competition.

Perhaps unsurprisingly given the above observation, both types of uppercut exhibited the greatest peak values for shoulder-joint angular velocity, with the lead uppercut also generating the highest peak elbow-joint angular velocity values of all punch types. As the kinematics of the lead uppercut have not been described previously, this is a novel finding.

However, with regards to the moments of peak shoulder and elbow joint angular velocities, only straight punches (jab and rear-hand cross) exhibited a proximal-to-distal sequence of the upper limbs. This is in agreement with previous studies that have reported how shoulder angular velocity peaks prior to the elbow during the rear-hand cross (Cheraghi et al., 2014; Turner et al., 2011). That such a sequence was evident for the jab also has not been observed before. It is suggested that hooks and uppercuts failed to exhibit a proximal-to-distal sequence due to the ‘fixed’ elbow positions associated with these punch types. Indeed, during straight punches, the elbow joint rapidly extends after the punching arm has already started accelerating towards the target via angular velocities generated at the shoulder joint (Cheraghi et al., 2014; Jessop & Pain, 2016). However, during hooks and uppercuts, the elbow is flexed to ‘fixed’ ~90° angle whilst the shoulder exhibits a rapid combination of abduction followed by flexion, protraction, and adduction from INITIATION to CONTACT, which may explain why peak angular velocities at the shoulder joint were markedly higher than those at the elbow across hooks and uppercuts. Consequently, it appears that peak elbow joint angular velocity occurs prior to the elbow’s ~90° position during hooks and uppercuts, and may assist in generating additional kinetic energy that, in conjunction with the angular velocities generated at the shoulder, accelerate the fist rapidly towards the target.

The peaks and timing of peak angular joint velocities for the shoulder and elbow, respectively, provide noteworthy information regarding the role of each joint across different punches and the degree to which they contribute to the end product of a punch (fist velocity and delivery time). This data provides useful information for coaches and boxers that may assist in the development of resistance training strategies. More specifically, resistance training strategies designed to augment angular velocities generated at the shoulder and elbow across various punch-specific positions (e.g. shoulder abducted to 90° relative to the torso for lead and rear hooks), and subsequently, the ‘damage’ potential of specific punch types.

Kinetic (GRF and impulse) variables

Based on previous studies which have highlighted the importance of the lead leg to lead hand punches and the rear leg to rear hand punches (Cheraghi et al., 2014; Turner et al, 2011; Yan-ju et al., 2013), it was expected that the lead leg would produce greater GRF during lead hand punches, and likewise rear leg for rear hand punches. However, the current findings revealed that uppercuts (lead and rear) generated the greatest peak resultant GRF values for the lead leg across punch types (see Table 1). Moreover, it was interesting to find that both uppercuts produced greater peak lead leg resultant GRF values than straight and hook punches. In the absence of related research to assist interpretation for this finding, it is suggested that force orientation is a contributory factor in such movements (Bahamonde & Knudson, 2001; Morin, Edouard & Samozino, 2011; Plessa, Rousanoglou & Boudolos, 2010). That is, uppercuts (lead and rear) may generate the greatest peak lead leg resultant GRF owing to the larger peak lead leg vertical GRF values recorded for these punch types (in comparison to straights and hooks), alongside the predominantly vertical trajectory of the fist and a potential symbiotic relationship between these two characteristics.

That the rear uppercut generated higher peak lead leg resultant GRF than the jab and lead hook, respectively, was unexpected, as was the lead hook producing the greatest vertical impulse, while the rear hook generated the largest net braking impulse. It is possible that these findings relate to the influence of the lead leg in producing a stable base from which to generate force proximally to the distal segments (i.e. the fist) (Cabral et al., 2010). Such a role has been reported for other activities requiring movements with lower-body kinematics similar to those of rear hand punches (i.e. triple extension of the hip, knee and ankle; trunk rotation; rapid projection of the arm). For example, Bartonietz (1994) noted that the lead leg produced forces up to three times that of the rear leg in shot putting (no values though reported), while McCoy et al. (1984) determined ~95% of 'shot velocity' (i.e. velocity of the shot put when released from the hand) was influenced by vertical braking forces produced by the lead leg. Furthermore, the majority of lead leg GRF and impulse was concentrated in a vertical direction (see Table 1 and Figure 11), which is similar to findings observed in the above activities and baseball pitching (MacWilliams, Choi, Perezous, Chao & MacFarland, 1998). The considerable vertical GRF, net braking, and vertical impulse result from the extensive braking demands (rapid eccentric muscular contractions to prevent excessive knee flexion) that assist in facilitating the propulsive vertical forces generated by the rear leg to travel superiorly to the distal segments of the body (i.e. fist/hand) (Williams, 2012). This corroborates previous boxing research which has highlighted that during the rear-hand cross punch, the ability of a boxer to maintain a rigid lead leg (through the production of vertical anterior-posterior braking forces (i.e. impulse)) during a punch has assists in the transmission of force from the lower limbs to the arm/hand segments via the kinetic chain (Cheraghi et al., 2014; Turner et al., 2011). The current findings implicate the rigidity and braking forces of the lead leg play a crucial role for both the lead and rear uppercut, and that they are more evident than for the rear-hand cross.

The observed higher GRF values of the rear leg, rear-hand cross, rear hook and rear uppercut techniques than the lead hook and lead uppercut, confirm the importance of the rear leg to rear hand punches noted previously (Cheraghi et al., 2014; Filimonov et al., 1985; Gulledge & Dapena, 2008; Turner et al. 2011). However, that the rear leg produced ~71% of the total GRF during the jab - greater than for any other punch type - was a novel finding. It is plausible to suggest that rear leg resultant GRF is less reliant on trunk rotation and upper-body stretch-shortening cycle characteristics, and instead, requires a high degree of rear leg resultant GRF to propel the fist rapidly along the anterior-posterior axis towards the opponent/target. Moreover, as the lead hook generated the largest vertical impulse and the rear hook the largest net propulsive impulse for the rear leg, it appears that these two punches produced the highest forces over the duration of each punch from INITIATION to CONTACT.

Previous research has reported the importance of impulse to explosive dynamic movements (Davies, Orr, Halaki & Hackett, 2016; Suchomel & Sole, 2017), and, more specifically, that enhancing the braking (antero-posterior and vertical) impulse of the lead leg may increase the force of a punch owing to an increase in velocity, and subsequently momentum (mass x velocity) (Turner et al., 2011). Indeed, it is suggested that the greater the vertical and net propulsive impulse produced by the rear leg, the greater the overall momentum and peak fist velocities generated. Consequently, it seems reasonable to suggest that the more GRF a boxer can produce from the initiation of a punch to the point of impact with the target, the larger the degree of energy generated by the kinetic chain. In turn, this yields greater resultant joint angular velocities generated by the upper-limbs (shoulder and elbow) and linear velocity of the fist towards the target. Future research should investigate the role of impulse to maximal punching, its relationship to GRF during maximal punching, and assess whether enhancing this kinetic variable can improve the characteristics of maximal punching performance.

Relationships between kinematic and kinetic variables

As expected, lead hook peak resultant fist velocity exhibited a significant (moderate) relationship with peak lead leg resultant GRF, signifying the influence of the vertical GRF produced by the lead leg. On this evidence, it is proposed that as part of training/technical practice, boxers aiming to increase the velocity of the fist and the damage-causing capabilities of this punch attempt to focus deliberately on generating force through the lead leg during the initiation and delivery of the lead hook. In addition, as previous research has highlighted the importance of lower-body strength to maximal punching (Loturco et al., 2014, 2016; Stanley, 2014; Zekas, 2016), coaches and boxers should consider the implementation of axial-loaded lower-body resistance exercises (e.g. squats, deadlifts, cleans, lunges) that emphasise triple extension (hip, knee and ankle) force production (Lenetsky et al., 2013; Turner et al., 2011), alongside traditional skill-based practice in order to enhance the peak vertical and resultant GRF potential of the lead leg.

Peak shoulder joint angular velocity also exhibited a moderate relationship with peak lead hook fist velocity, confirming the findings of Piorkowski (2009. It has been suggested that rear-hand crosses (Karpilowski, Nosarzewski, Staniak &

Trzaskoma, 2001), lead and rear hooks (Piorkowski et al., 2011; Whiting et al., 1988), and lead and rear uppercuts (Cabral et al., 2010) produce a stretch-reflex (via the SSC) at the shoulder joint which potentiates the ensuing concentric muscular contraction, and subsequently, fist velocity. Therefore, it would appear that resistance training exercises that improve a boxer's ability to rapidly abduct and adduct the punching arm may enhance the end-point velocity of the fist, and subsequently, its damage-causing potential. Furthermore, as the upper-body kinematics of punching comprise a multitude of joint motions, including shoulder adduction, abduction, flexion and extension (Cabral et al., 2010; Piorkowski et al., 2011), a boxer's training regimen should aim to incorporate ballistic resistance exercises that enhance speed and velocity characteristics of the musculature (deltoid, pectoralis major and minor, latissimus dorsi, and serratus anterior) that facilitate such motions, alongside regular technical practice (Piorkowski et al., 2011; Turner et al., 2011; Veegera & Van Der Helma, 2007).

The significant association between peak elbow angular velocity and lead hook peak resultant fist velocity has not been documented in previous research, and it is suggested that, in a similar manner to the shoulder joint, the elbow joint exhibits a stretch-reflex following INITIATION that facilitates the generation of large peak fist velocities. Indeed, at the onset of INITIATION, the elbow may extend slightly from its flexed ~90° angle as the shoulder abducts before rapidly adducting as the fist is projected towards the target. Although further research is required to establish if kinetic and kinematic variables associated with maximal punching performance are optimised if the elbow joint is extended and flexed rapidly or fixed at a ~90° angle, enhancing the eccentric strength and SSC efficiency of the musculature surrounding the elbow joint would appear to increase stability and force production potential of the lead hook (Cormie, McGuigan & Newton, 2011; Zatsiorsky & Kraemer, 2006).

Given the findings of Piorkowski et al. (2011) it was unsurprising to observe the link between peak jab resultant fist velocity and elbow joint angular. This likely occurs as a consequence of the jab often being less reliant upon SSC characteristics at the shoulder joint and trunk in order to minimise its delivery time, and therefore enhance its likelihood of striking the opponent before they can defend/evade (Haislet, 1968; Hickey, 2006). It would appear that enhancing a boxer's ability to extend the punching arm as rapidly and forcibly as possible (elbow extension) may increase peak jab fist velocity, and consequently, could improve competitive performance considering the jab to the head of an opponent is the most frequently executed punch within competitive bouts (Davis et al., 2015; Davis et al., 2017; Thomson & Lamb, 2016). Moreover, increasing the rate of force development (RFD) of the elbow extensors (via elastic resistance training) has been shown to improve peak jab velocity as much as 11% ($P < 0.01$) in competitive boxers, (Markovic, Suzovic, Kasum & Jaric, 2016). Therefore, it is recommended that boxers include resistance exercises in their training programme that increase the strength of the tricep brachii musculature (primary muscle group responsible for elbow extension) to improve elbow joint velocity, and subsequently, peak jab fist velocity.

Limitations

Though the current study provides a comprehensive analysis of the biomechanical characteristics associated with maximal punching, there are two limitations to acknowledge. Firstly, the experience and sub-elite ability level of the boxers in the present study suggests the findings herein might not generalise to higher standards of boxing. Therefore, future research should assess the punching performance of a more heterogeneous sample to identify key kinetic and kinematic differences that might exist according to ability and experience levels.

Secondly, the position of the force plates relative to the punch target necessitated that the taller boxers in the sample (≥ 1.8 m; n = 6) made contact with the target before reaching full elbow extension during straight punches. As self-selected punching distances have been shown to produce superior (P < 0.05) punch kinetics values than fixed distances (Loturco et al., 2014; Loturco et al., 2016; Neto et al., 2012), future research should seek to analyse the kinetics and kinematics of maximal punching whereby boxers are permitted to punch from a self-selected distance relative to the target.

Conclusion

In appraising the kinetic and kinematic characteristics of six traditional punch techniques implemented within amateur boxing, the present study has revealed that: (i) the lead hook produced the greatest peak resultant fist velocity values; (ii) the jab recorded the shortest delivery time; (iii) peak lead and rear leg resultant GRF were comparable across all punch types except for the jab, with force primarily applied in a vertical direction; (iv) punch-specific inter-relationships exist between peak fist and joint angular velocities, and peak fist velocities and GRF. Whilst alone these findings advance our biomechanical understanding of maximal punching, there is now scope to investigate the links between boxers' physical qualities and the key kinetic and kinematic variables, leading potentially to the development of punch-specific strength and conditioning strategies.

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Table 1. Reliability statistics for the identification of INITIATION (time between the moment of force plate contact to the point of punch initiation).

	Test	Retest	TE (ms)	CV (%)	95% LoA (ms)
Jab	1.28 ± 1.21	1.28 ± 1.22	0.01	2.69	0.08± 0.05
Rear-hand cross	1.46 ± 1.0	1.45 ± 1.0	0.01	0.10	0 ± 0.05
Lead hook	0.95 ± 1.04	0.94 ± 1.04	0.01	3.95	0 ± 0.04
Rear hook	0.82 ± 0.66	0.82 ± 0.66	0.01	2.64	0 ± 0.03
Lead uppercut	1.31 ± 0.87	1.32 ± 0.86	0	4.3	0 ± 0.02
Rear uppercut	0.81 ± 0.83	0.80 ± 0.82	0.01	2.77	0.01 ± 0.05

Note: ms = milliseconds

Table 3. Correlations (*r*) between peak resultant fist velocity (FV) of six punch types and kinematic and kinetic variables.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Punch delivery time (ms)	0.45	0.34	-0.41	0.39	-0.08	0.18
Peak shoulder joint angular velocity (deg/s)	0.35	0.05	0.55*	0.40	0.08	-0.04
Peak elbow joint angular velocity (deg/s)	0.78*	0.02	0.57*	0.19	-0.23	-0.16
Peak lead leg GRF (N/kg)	-0.24	0.12	0.56*	0.28	0.22	-0.09
Rear leg GRF (peak)	0.11	0.35	0.10	0.28	-0.46	-0.05
Total lead leg net braking impulse (N/s/kg)	0.30	0.46	0.25	0.20	0.21	0.27
Total lead leg vertical impulse (N/s/kg)	0.12	-0.13	0.06	-0.00	0.04	-0.42
Total rear leg net propulsive impulse (N/s/kg)	0.41	0.35	0.09	0.40	0.10	0.22
Total rear leg vertical impulse (N/s/kg)	0.47	0.35	0.04	0.31	0.12	0.15

* denotes statistically significant ($P < 0.01$)

Table 2

Table 2a. Kinematic variable values of six punch techniques.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Punch delivery time (ms)	405 ± 150 (*LH, RH, LU, RU*)	495 ± 150	657 ± 145 (*J*)	586 ± 0.96 (*J*)	627 ± 103 (*J*)	606 ± 100 (*J*)
Peak fist velocity (m/s)	5.85 ± 0.85 (*C, LH, RH, RU*)	6.97 ± 0.86 (*J, LH, RH, RU*)	11.95 ± 1.84 (*J, C*)	11.48 ± 1.90 (*J, C*)	10.60 ± 2.30	11.55 ± 1.72 (*J, C*)
Peak shoulder joint angular velocity (deg/s)	691.1 ± 135.5 (*LU, RU*)	534.5 ± 207.8 (*LH, RH, LU, RU*)	845.6 ± 143.0 (*C, LU, RU*)	948.9 ± 228.0 (*C*)	1062.1 ± 186.2 (*J, C, LH*)	1069.8 ± 104.5 (*J, C, LH*)
Peak elbow joint angular velocity (deg/s)	560.6 ± 197.4	399.6 ± 171.8	527.5 ± 183.0	522.2 ± 212.5	651.0 ± 357.5	539.3 ± 139.9
Timing of peak shoulder joint angular velocity (% of movement	87 ± 7	91 ± 8	92 ± 12	97 ± 2	96 ± 1	96 ± 1
Timing of peak elbow joint angular velocity (% of movement)	98 ± 2	99 ± 1	81 ± 10	84 ± 11	76 ± 5	75 ± 7

Note: Data are presented as mean ± SD.

J = significantly different to the jab ($P < 0.01$).
C = significantly different to the rear-hand cross ($P < 0.01$).
LH = significantly different to the lead hook ($P < 0.01$).
RH = significantly different to the rear hook ($P < 0.01$).
LU = significantly different to the lead uppercut ($P < 0.01$).
RU = significantly different to the rear uppercut ($P < 0.01$).

Table 2b. Kinetic variable values of six punch techniques.

	Jab	Rear-hand cross	Lead hook	Rear hook	Lead uppercut	Rear uppercut
Peak lead leg GRF (N/kg)	0.63 ± 0.17 (*C, LH, RH, LU, RU*)	1.06 ± 0.26 (*J, RU*)	1.09 ± 0.24 (*J*)	1.13 ± 0.20 (*J, RU*)	1.35 ±0.27 (*J*)	1.35 ± 0.26 (*J, C, RH*)
Peak rear leg GRF (N/kg)	1.56 ± 0.35 (*C, LH, RH, LU*)	1.21 ± 0.27 (*J*)	0.96 ± 0.23 (*J*)	1.10 ± 0.23 (*J*)	1.15 ± 0.32 (*J*)	1.20 ± 0.28
Total lead leg net braking impulse (N/s/kg)	-10.1 ± 8.9 (*C, RH, LU*)	-62.5 ± 32.4 (*J*)	-32.6 ± 27.3 (*RH*)	-85.8 ± 37.8 (*J, LH, LU*)	-44.1± 20.8 (*J, RH*)	-64.4 ± 56.4
Total lead leg vertical impulse (N/s/kg)	89.7 ± 89.8 (*LH, RH, LU, RU*)	150.8 ± 77.1 (*LH, LU, RU*)	386.8 ± 160.2 (*J, C*)	248 ± 98.3 (*J*)	368.4 ± 120.9 (*J, C*)	297 ± 122.7 (*J, C*)
Total rear leg net propulsive impulse (N/s/kg)	29.2 ± 20.1 (*C, RH*)	66.6 ± 38.4 (*J, LH*)	17.7 ± 27.7 (*C, RH, LU*)	77.9 ± 34.7 (*J, LH*)	45.8 ± 25.2 (*LH*)	64.6 ± 54.3
Total rear leg vertical impulse (N/s/kg)	187.8 ± 121.0	239.3 ± 158.4	268 ± 141.8	255.3 ± 102.0	256.6 ± 115.8	258.1 ± 114.6

Note: Data are presented as mean ± SD.

J = significantly different to the jab ($P < 0.01$).
C = significantly different to the cross ($P < 0.01$).
LH = significantly different to the lead hook ($P < 0.01$).
RH = significantly different to the rear hook ($P < 0.01$).
LU = significantly different to the lead uppercut ($P < 0.01$).
RU = significantly different to the rear uppercut ($P < 0.01$).

Figure

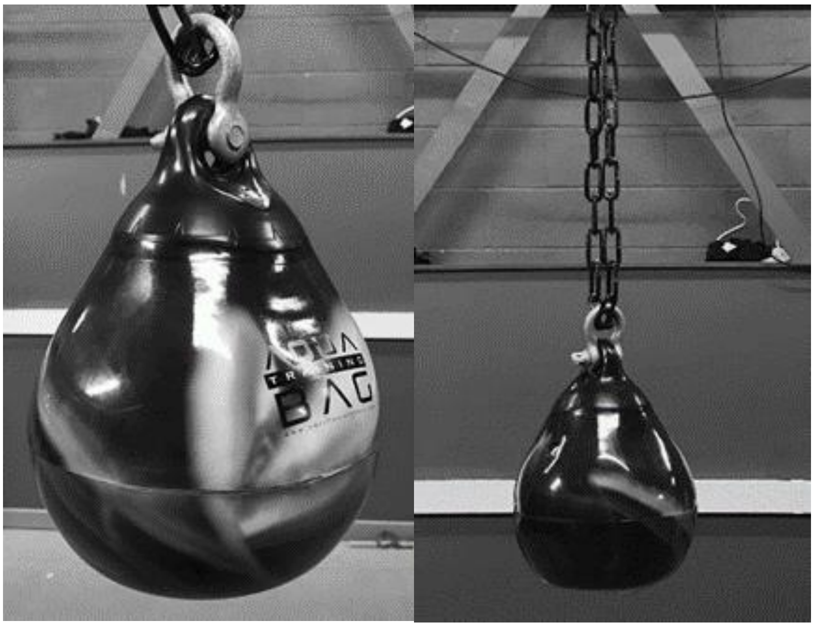

Figure 1. Aqua Bag 'Headhunter' punch target.

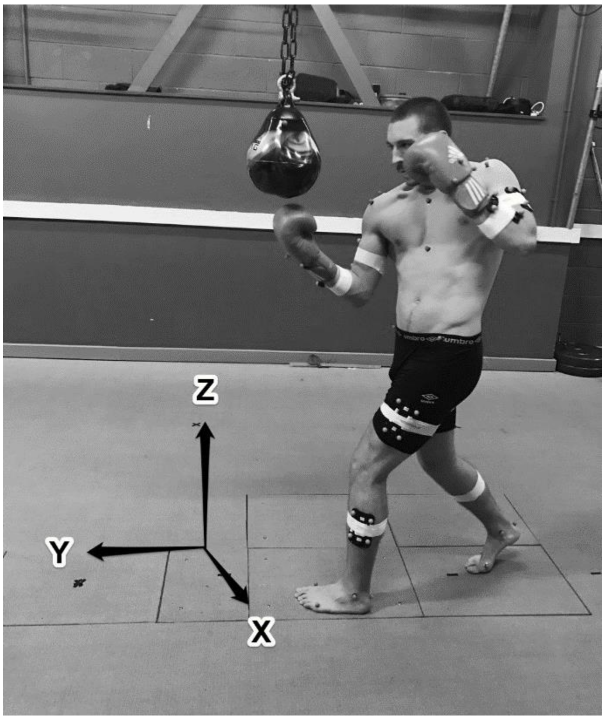

Figure 2. Laboratory coordinate system and punch target

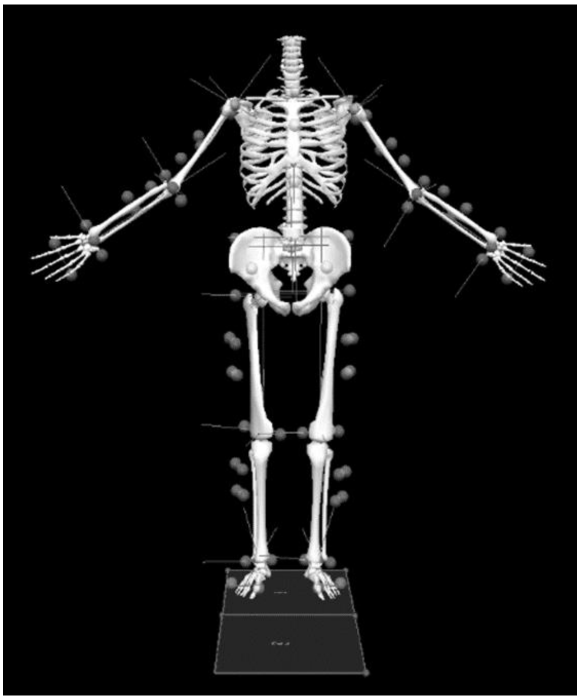

Figure 3. Local coordinate system of the adapted marker model.

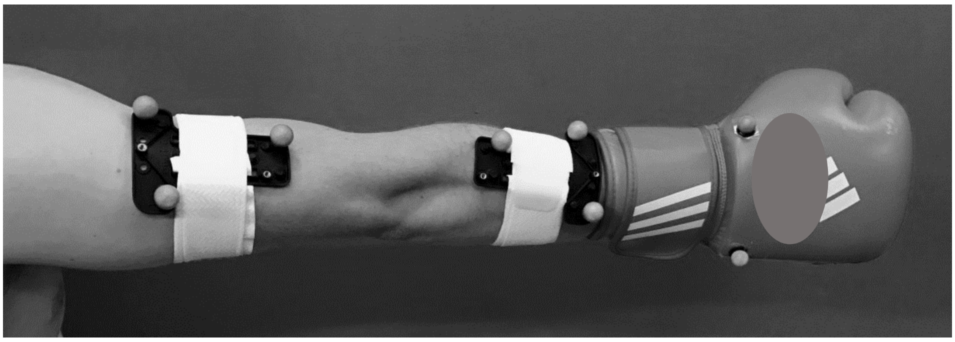

Figure 4. Upper-extremity marker set

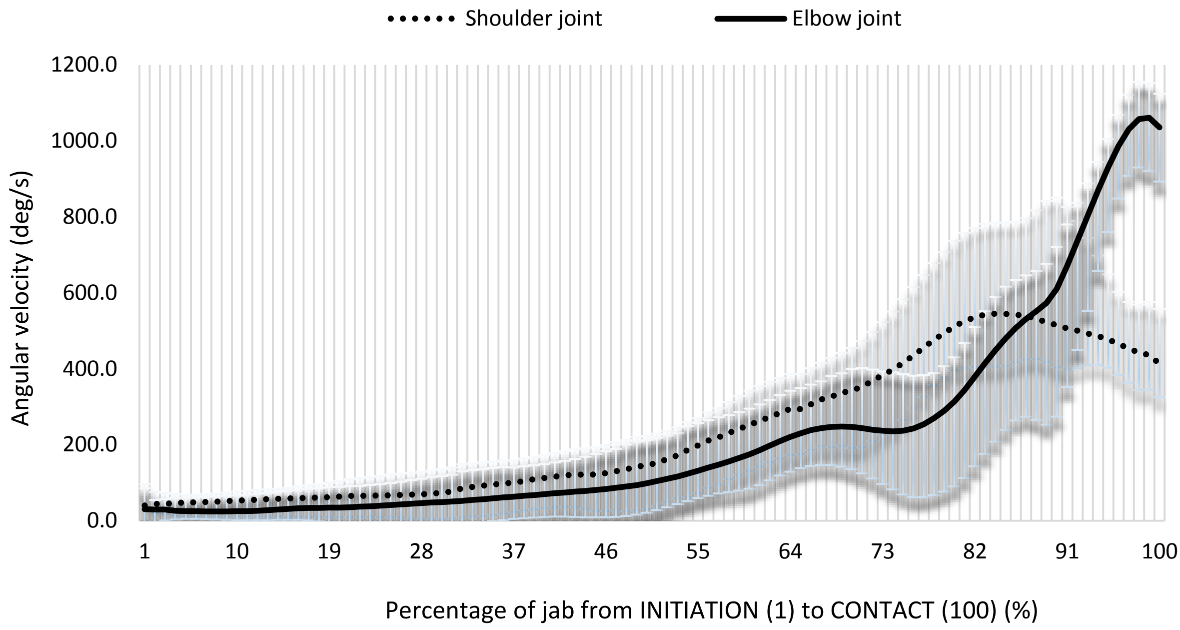

Figure 5. Mean jab shoulder and elbow joint angular velocities from INITIATION to CONTACT

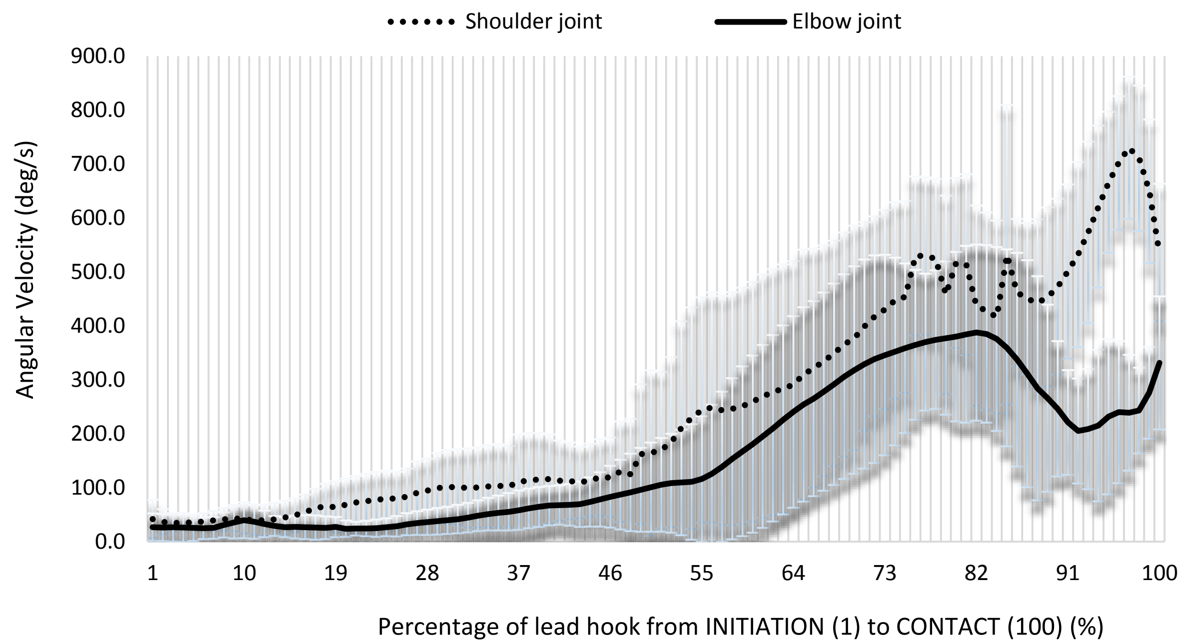

Figure 6. Mean lead hook shoulder and elbow joint angular velocities from INITIATION to CONTACT

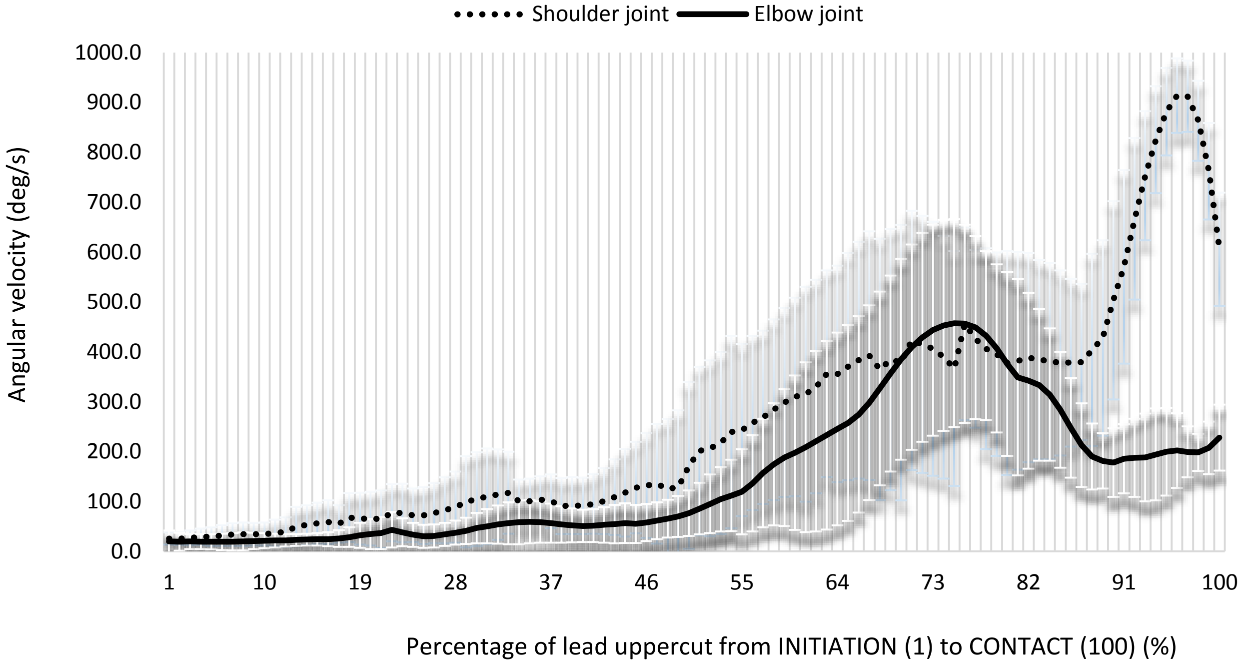

Figure 7. Mean lead uppercut shoulder and elbow joint peak angular velocities from INITIATION to CONTACT

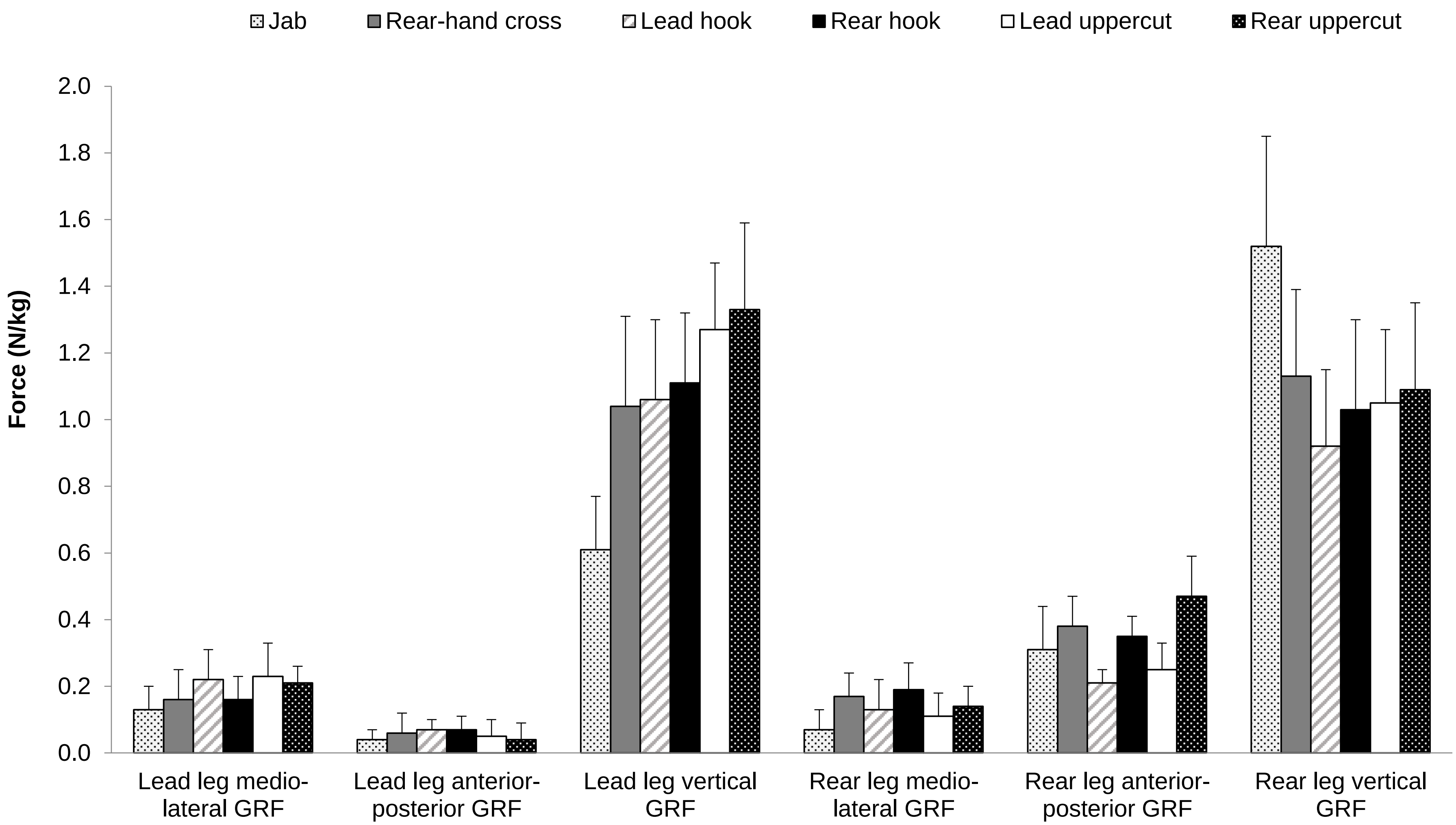

Figure 8. Peak lead and rear leg GRF (mean + SD) in mediolateral, anteriorposterior and vertical planes of motion across punch types (in accordance with the laboratory co-ordinate system).