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Evaluating Methods of Assessing Force and Velocity during Punching Specific Movements

Dissertation

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I declare that I complied this dissertation on my own under my supervisor's leadership, using only the listed sources and literature. I did not use this dissertation to obtain another academic degree.

Prague, June, 2023 ……………………………
Signature

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Abstract

Title: Evaluating Methods of Assessing Force and Velocity during Punching Specific Movements

Objectives: This dissertation had three main objectives:

1. To determine the ability of different commercially available punch trackers (Corner, Everlast, and Hykso) to recognize specific punch types (lead and rear straight punches, lead and rear hooks, and lead and rear uppercuts) thrown by trained and untrained punchers.
2. To determine the validity of three commercially available punch trackers (Corner, Hykso, and StrikeTec) for monitoring punch velocity and force during rear straight punches, rear hooks, and rear uppercuts performed at lower and higher intensities by trained and untrained punchers.
3. To determine the reliability and load-velocity profiles of three different landmine punch throw variations (seated without trunk rotation [LPwo], seated with trunk rotation [LPw], and standing whole body [LP]) with different loads (20.0 kg, 22.5 kg, and 25.0 kg), all with the dominant (DH) and non-dominant hand (NH).

Methods: Due to three independent studies in this dissertation, the methods are divided into three sections, each connected to the objectives mentioned above:

1. Ten trained and 11 untrained punchers different punch combinations, and punch trackers data were compared to data from video recordings to determine how well each punch tracker recognized the punches that were actually thrown. Descriptive statistics and multilevel modelling were used to analyze the data.
2. Twenty healthy males performed six individual rear straight punches, rear hooks, and rear uppercuts against a wall-mounted force plate. Punch trackers variables were compared with the peak force of the force plate and to the peak (QPV) and mean (QMV) assessed through Qualisys 3-dimensional tracking. For each punch tracker variable, Pearson's correlation coefficient, mean absolute percentage error (MAPE), and mean percentage error (MPE) were calculated.
3. In a quasi-randomized order, fourteen boxers performed three repetitions of each variation with DH and NH, with maximal effort and 3 minutes inter-set rest. Peak velocity (PV) was measured via GymAware power tool. The intra-session

reliability of each variation-load-hand combination was determined along with the intraclass correlation coefficients and their 95% confidence intervals. Additionally, a 2(hand)*3(variation) repeated measures ANOVA assessed the load-velocity profile slope.

Results: The main results of this dissertation were as follows:

1. The Corner, Everlast, and Hykso detected punches more accurately in trained punchers compared to untrained punchers, evidenced by a lower percentage error in trained punchers ($p = 0.007$). The Corner, Everlast, and Hykso detected straight punches better than uppercuts and hooks, with a lower percentage error for straight punches ($p < 0.001$). The recognition of punches with Corner and Hykso depended on punch order, with earlier punches in a sequence recognized better.
2. There were no strong correlations between punch tracker data and gold-standard force and velocity data. However, Hykso "velocity" was moderately correlated with QMV (r = 0.68, MAPE = 0.64, MPE = 0.63) and QPV (r = 0.61, MAPE = 0.21, MPE = -0.06). Corner Power G was moderately correlated with QMV (r = 0.59, MAPE = 0.65, MPE 0.58) and QPV (r = 0.58, MAPE 0.27, MPE = -0.09), but Corner "velocity" was not. StrikeTec "velocity" was moderately correlated with QMV (r = 0.56, MAPE = 1.49, MPE = 1.49) and QPV (r = 0.55, MAPE = 0.46, MPE = 0.43).
3. Most variations were highly reliable (ICC > 0.91), with the NH being as reliable or more reliable than the DH. Very strong linear relationships were observed for the group average for each variation ($R^2 \geq 0.96$). However, there was no variation*hand interaction for the slope, and there was no main effect for variations or hands.

Keywords: boxing, combat sports, punch velocity, punch trackers, landmine punch throw

Abstrakt

Název: Hodnocení metod pro posuzování síly a rychlosti během úderů

Cíle: Tato disertační práce má tři hlavní cíle:

1. Určit validitu vybraných komerčně dostupných přístrojů pro monitorování charakteristik úderu (Corner, Everlast and Hykso) rozpoznávat typy úderů (přední a zadní přímé údery, přední a zadní háky a přední a zadní zvedáky) u probandů se zkušenostmi s bojovými sporty a u probandů bez zkušeností s bojovými sporty.
2. Určit validitu vybraných komerčně dostupných přístrojů pro monitorování charakteristik úderů (Corner, Hykso a StrikeTec) pro monitorování rychlosti a síly úderu při zadních přímých úderech, zadních hácích a zadních zvedáků u probandů se zkušenostmi s bojovými sporty a u probandů bez zkušeností s bojovými sporty.
3. Určit reliabilitu a profil zatížení a rychlosti při různých variantách testu landmine punch throw (v sedě bez rotace trupu [LPwo], v sedě s rotací trupu [LPW] a v provedení celého těla [LP]) s různými zatíženími (20,0 kg, 22,5 kg a 25,0 kg) v provedení dominantní (DH) a nedominantní (NH) ruku.

Metody: Vzhledem ke třem nezávislým studiím, ze kterých se skládá tato disertační práce jsou metody rozděleny do tří částí, z nichž každá navazuje na předchozí cíl:

1. Deset probandů se zkušenostmi a 11 probandů bez zkušeností s bojovými sporty provedlo odlišné kombinace boxerských úderů. Data získaná z přístrojů pro monitorování charakteristik úderů byla porovnána s videozáznamem, získaným během provádění jednotlivých kombinací za účelem určení, jak přesně jednotlivé přístroje pro monitorování charakteristik úderů rozpoznávají provedené údery. Pro analýzu dat byla použita deskriptivní analýza a lineární model se zvýšenými efekty.
2. Dvacet probandů provedlo šest individuálních přímých zadních úderů, zadních háků a zadních zvedáků do silové desky umístěné na zdi. Hodnoty z přístrojů pro monitorování charakteristik úderů byly porovnány s maximální silou získanou ze silové desky, maximální (QPV) a průměrnou rychlostí (QMV) získanou z 3D kinematické analýzy. Pro každou hodnotu ze sledovačů charakteristik úderů byl vypočítán Pearsonův korelační koeficient, střední absolutní procentuální chyba (MAPE) a střední procentuální chyba (MPE).

3. Čtrnáct boxerů v náhodném pořadí provedlo 3 opakování pro každou z variant landmine punch throw. Každá z variant byla provedena s maximálním úsilím DH a NH s 3minutovou dobou odpočinku mezi jednotlivými variantami. Maximální rychlost (PV) byla měřena pomocí lineárně pozičního transduktoru GymAware. Byla vypočítána reliabilita každé kombinace varianty-zátěže-ruce spolu s koeficientem vnitrotřídní korelace (ICC) s jejich 95% konfidenčními intervaly. Dále byla provedena 2(ruka)*3(varianta) analýza rozptylu ANOVA s opakovanými měřeními pro posouzení sklonu lineární přímky.

Výsledky: Hlavní výsledky disertační práce jsou následující:

1. Všechny přístroje pro monitorování charakteristik úderů zaznamenávaly přesněji údery (dáno nižší procentuální chybou [p = 0,007]) u probandů se zkušenostmi s bojovými sporty v porovnání s probandy bez těchto zkušeností. Dále všechny přístroje pro toto monitorování lépe zaznamenávaly přímé údery v porovnání s háky a zvedáky, a to s nižší procentuální chybou u přímých úderů (p < 0,001). Rozpoznávání úderů u přístrojů Corner a Hykso záviselo na pořadí úderů v kombinaci, přičemž v začátku kombinace byly údery rozpoznávány lépe.
2. Nebyly zjištěny vysoké korelace mezi daty získanými ze sledovačů, silové desky a 3D kinematiky. Nicméně „rychlost" u přístroje Hykso středně korelovala s QMV (r = 0,68, MAPE = 0,64, MPE = 0,63) a QPV (r = 0,61, MAPE = 0,21, MPE = -0,06). Power G u přístroje Corner středně korelovala s QMV (r = 0,59, MAPE = 0,65, MPE 0,58) a QPV (r = 0,58, MAPE 0.27, MPE = -0,09), ale “rychlost” u tohoto přístroje ne. “Rychlost” u StrikeTec středně korelovala s QMV (r = 0,56, MAPE = 1,49, MPE = 1,49) a QPV (r = 0,55, MAPE = 0,46, MPE = 0,43).
3. Většina variant dosáhla vysoké reliability (ICC > 0,91), nicméně NH dosahovala stejných nebo lepších výsledků v porovnání s DH. Dále byly pozorovány silné lineární vztahy pro průměr celé skupiny pro každou variantu ($R^2 \geq 0.96$). Nicméně nebyla zjištěna interakce mezi variantou a rukou pro sklon lineární přímky, včetně efektu pro variantu nebo ruku.

Klíčová slova: box, bojové sporty, rychlost úderu, přístroj pro monitorování charakteristik úderu, landmine punch throw

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Chapter 4. Punch trackers: correct recognition depends on punch type and training experience

α	Alfa
CM	Centimeter
CPT	Corner
EPT	Everlast
HPT	Hykso
KG	Kilogram
LH	Lead hook
LS	Lead straight
LUC	Lead uppercut
MAPE	Mean absolute percentage error
MPE	Mean percentage error
RH	Rear hook
RS	Rear straight
RUC	Rear uppercut
PT	Punch tracker
SPT	StrikeTec
TOST	Two one-side tests
TR	Trained punchers
UNTR	Untrained punchers
Y	Year

Chapter 6. Validity of commercially available punch trackers

CM	Centimeter
Hz	Hertz
KG	Kilogram
MAPE	Mean absolute percentage error
MPE	Mean percentage error
QMV	Qualisys mean velocity
QPV	Qualisys peak velocity
r	Pearson’s correlation coefficient
RH	Rear hook
RS	Rear straight
RUC	Rear uppercut
QMV	Qualisys mean velocity
QPV	Qualisys peak velocity

Chapter 8. Reliability of three landmine punch throw variations and their load-velocity relationships performed with the dominant and non-dominant hands

CM	Centimeter
DH	Dominant hand
ICC	Intraclass correlation coefficient
KG	Kilogram
LCI	Lower confidence interval
LP	Whole body landmine punch throw
LPw	Landmine punch throw in seated position with trunk rotation
LPwo	Landmine punch throw in seated position without trunk rotation
NH	Non-dominant hand
PV	Peak velocity
SD	Standard deviation
Y	Years
UCI	Upper confidence interval

List of peer-reviewed publications included in this thesis

Chapter 4. Omcirk Dan, Větrovský Tomáš, Pádecký Jan, Vanbelle Sophie, Maleček Jan, Tufano James. Punch trackers: correct recognition depends on punch type and training experience. *Sensors*, 2021. Doi: 10.3390/s21092968 **(IF 3.576)**

Chapter 6. Omcirk Dan, Větrovský Tomáš, Pádecký Jan, Maleček Jan, Tufano James. Validation of commercially available punch trackers. The *Journal of Strength and Conditioning Research*, 2023. Doi: 10.1519/JSC.0000000000004535 **(IF 4.415)**

Chapter 8. Omcirk Dan, Větrovský Tomáš, O'Dea Cian, Ruddock Alan, Wilson Daniel, Maleček Jan, Pádecký Jan, Tufano James. Reliability of three landmine punch throw variations and their load-velocity relationship performed with the dominant and non-dominant hands. *International Journal of Sports Physiology and Performance*, 2023. (under review)

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Appendix 4: Omcirk D, Vetrovsky T, Padecky J, Vanbelle S, Malecek J, Tufano JJ. Validation of velocity measurements from different commercial punch trackers and their relationship to punch force. *National Strength and Association Annual Conference*, Las Vegas, USA, July 2020. *conference cancelled due to COVID-19, but abstract still accepted and presented virtually.

Appendix 5: Omcirk D, Vetrovsky T, Padecky J, Vanbelle S, Malecek J, Tufano JJ. Can commercially punch trackers actually recognize different punch types correctly? *National Strength and Association Annual Conference*, Las Vegas, USA, July 2020. *conference cancelled due to COVID-19, but abstract still accepted and presented virtually.

Appendix 6: Omcirk D, Vetrovsky T, O'Dea C, Ruddock A, Wilson D, Malecek J, Padecky J, Tufano JJ. The load-velocity profiles of different landmine punch throw variations. *National Strength and Association Annual Conference*, New Orleans, LA, USA, July 2022.

Appendix 7: Omcirk D, Vetrovsky T, O'Dea C, Ruddock A, Wilson D, Malecek J, Padecky J, Tufano JJ. Intra-session reliability of different landmine punch throw variations for upper body testing. *National Strength and Association Annual Conference*, New Orleans, LA, USA, July 2022.

1 Introduction

The winner and loser of many combat sports, regardless of the discipline, can often be determined by a single punch. Although winning a fight could somewhat indicate how well that fighter performed, simply judging whether they won or lost does not encapsulate their overall performance. As such, coaches can neither "monitor" a fighter's performance based on their win-loss ratio, nor determine whether a fighter's performance improves over time based on the results of competitions only. Therefore, coaches need tools to assess different performance variables in combat sports (e.g., hand speed and punch force) to indicate whether or not sport-specific training adaptations occur over a long period of time. These sport-specific training adaptations can be assessed with fundamental strength and conditioning movement patterns in addition to real-world sport performance. However, each specific task that is assessed needs a specific test and a specific testing devices which will provide data regarding different aspects of a fighter's performance.

One example of a testing device that is meant to assess a specific performance variable is a punch tracker. These commercially available smart technologies are used to measure punch characteristics (e.g., force, velocity, power, punch type, punch count, etc.) in real-life conditions such as during training (e.g., shadow boxing, bag work, sparring, etc.) or even during competition. In 2018, in the early phases of this dissertation, punch trackers were becoming more popular despite research indicating that they valid tools that provided accurate information about punching performance. In fact, to the best my knowledge, there were not any studies which aimed to determine the validity of commercially available punch trackers.

Around the same time, the landmine punch throw (which is a unilateral exercise used to train and assess upper body ballistic performance) began to gain popularity in the strength and conditioning field. In fact, the landmine punch throw could be a useful movement to assess punch-related performance in the weight room, as the movement patterns are similar, and a linear position transducer can be used to track the velocity and resultant power of barbell when thrown. However, similar to punch trackers at the beginning of my dissertation journey, no research had investigated the reliability of the landmine punch throw, meaning the people were using it to assess performance without determining *if* it could be used to assess performance.

Therefore, the overarching aim of this dissertation was to determine the accuracy of commonly used field-based tools that assess force and velocity during punches and punch-specific movements (i.e., the landmine punch throw). Specifically, the main objectives of this dissertation were:

- To compare four commercially available punch trackers to determine their abilities to detect and recognize specific types of boxing punches thrown by trained and untrained punchers during standardized shadow boxing.
- To validate three commercially available punch trackers for tracking punch velocity and force during different types of rear punches thrown by trained and untrained punchers at higher and lower intensities.
- To determine the reliability of three landmine punch throw variations (arm, arm and trunk, and whole-body movement) each with three different loads (an Olympic barbell, and Olympic barbell +2.5 kg, and an Olympic barbell +5.0 kg) performed by dominant and non-dominant hand. This also allowed for an evaluation of an upper-body unilateral load-velocity profiles with the dominant and non-dominant hands (which is also timely and relevant, as the idea of load-velocity profiling had increased tremendously in recent years).

Following the Introduction (Chapter 1), the theoretical background is explained in Chapter 2, which also introduces important aspects of boxing with regards to the aims of this dissertation. Furthermore, to conclude Chapter 2, the current state of knowledge (around the period of staring this dissertation in 2018) about the possibilities of measuring force and velocity during punching specific movement are explained.

This dissertation includes three original research studies, each of which are presented in Chapter 4, Chapter 6, and Chapter 8, respectively. Chapter 3, Chapter 5, and Chapter 7 each summarize the previous study's (chapter's) main findings and show the logical transition into the ideas of the next study.

Chapter 4 is formed by the manuscript: *"Punch trackers: Correct recognition depends on punch type and training experience"*, doi: 10.3390/s21092968, published in 2021 in journal Sensors (IF = 3.576). The manuscript presented results that all of the tested punch trackers detected punches with more accuracy in trained than untrained punchers. Further, detecting straight punches was better compared to uppercuts and hooks. Additionally, the order of boxing punch within combinations have influence to the successful recognition.

Chapter 6 is formed by the manuscript: *"Validity of commercially available punch trackers"*, doi: 10.1519/JSC.0000000000004535, published in 2023 in the Journal of Strength and Conditioning Research (IF 4.415). Presented data indicates that none of the punch tracker variables are highly correlated with the gold-standard velocity and force measurement. However, based on this study, two punch trackers can be used to monitor peak velocity if potential users are willing to accept the errors that occur within.

Chapter 8 is formed by the manuscript: *"Reliability of different landmine punch throw variations and their load-velocity relationship performed with the dominant and non-dominant hands"*, currently submitted in 2023 in the International Journal of Sports Physiology and Performance (IF = 4.211). The results of this manuscript indicated that the landmine punch throw variations were highly reliable for both dominant and non-dominant hand. Further, the peak velocity was affected by variation, hand, and load. The goodness of fit were similar for the group average by each variation of landmine punch throw both dominant and non-dominant hand.

2 Theoretical part of dissertation

2.1 Boxing

Boxing is one of the most popular full-contact amateur and professional combat sports with a rich Olympic tradition (Bianco el al., 2013; Kruszewski et al., 2016). Therefore, it holds a significant place as one of the oldest competitive sports in human culture (Chaabène et al., 2015). In a boxing bout, two fighters engage in combat within designated boxing ring, aiming to strike their opponent (Piorkowski, Lees, Barton 2011) using punches delivered with their fists only (Gursoy, 2008) and evading punches thrown by the opponent (Dinu & Louis, 2020a; Whiting et al., 1988).

The primary objective of boxing is to secure victory either by knocking the opponent out through powerful punches or by accumulating more scoring points than the opponent. Boxers are awarded points for punches that land with sufficient force above the opponent's belt, excluding punches landing on the hands and shoulders (Blower, 2012). Boxing is characterized by high-intensity intermittent activity (Slimani et al., 2017), with a work-to-rest time ratio of 3:1 (International Boxing Federation, 2015; Khanna & Manna, 2006; Hanon et al., 2015) and 2:1 (International Boxing Association, 2022). Therefore, boxers must possess a high level of physical and physiological abilities to be proficient in the ring (Chaabène et al., 2015; Whiting et al., 1988).

Boxing is categorized into two main divisions based on the level of competition: amateur, also known as Olympic boxing, and professional boxing. The sport is governed by specific rules established by various organizations. The International Boxing Association serves as the independent governing body for amateur boxing, while professional boxing is regulated by four major organizations: the International Boxing Federation, World Boxing Council, World Boxing Association, and World Boxing Organization.

The main difference between amateur and professional boxing lies in the required equipment. Amateur boxers are mandated to wear a headguard and a vest during boxing bouts (International Boxing Association, 2022), whereas these protective measure and vest are not compulsory in professional boxing. Another distinction can be found in the number of rounds conducted during a boxing bout. In amateur boxing, Elite and Youth Men's and Women's divisions (aged 19 to 40 years) engage in three-round matches, with each round lasting three minutes and a one-minute inter-bout rest period between rounds

(International Boxing Association, 2022). In contrast, professional boxers can compete up to twelve rounds, each lasting three minutes with a one-minute inter-bout rest (International Boxing Federation, 2015) . Furthermore, differences between amateur and professional boxing include financial rewards and the chance to represent one's country in the Olympic Games. Apart from the level of competition, boxing is further categorized based on sex and age group.

Taking into consideration anthropometric parameters such as stature and body mass, weight classes were introduced in boxing (Morton et al., 2010). A study has shown a moderate and significant correlation between body mass and punch force (Dunn et al., 2022). In amateur boxing, Elite and Youth Men boxers are divided into thirteen weight classes, adhering to the rules set by the International Boxing Association. These classes range from minimumweight (from 46.0 to 48.0 kg) and lightweight (57.0 to 60.0 kg) to super heavyweight (over 92.00 kg). However, for the Olympic Games, the weight classes are represented by seven categories (from 46.0 to over 92.0 kg). As for Elite and Youth Women boxers, they are divided into twelve weight classes (from 45.0 to over 81.0 kg) in World Boxing Championships, for example, but six weight classes (from 45.0 to 75 kg) in the Olympic Games, according to the rules of the International Boxing Association. (International Boxing Association, 2023)

Boxing rules permit three basic types of punches: straights, hooks, and uppercuts (Dinu et al., 2020b; Beattie & Ruddock, 2022). Each of these punches can be executed in several modifications (Hatmaker & Werner, 2004). All of them can be delivered using either the lead or rear hand, and non-dominant or dominant hand, respectively (Hatmaker & Werner, 2004). Punch velocity and punch force are potential parameters that can determine the outcome of a boxing bout (Beránek et al., 2020). From this point of view, the boxing punch, especially its speed and force, emerges as one of the most important factors influencing a boxer's performance (Dinu & Louis, 2020a; Khasanshin, 2021), in addition to the physical and physiological aspects. Therefore, boxing training sessions should aim to improve aspects of the boxing punch, focusing on speed and force of the punch.

In general, boxing training sessions consist of specific boxing training techniques, such as shadow boxing (boxing without an opponent), sparring, pad punching, and bag work, as well as strength and conditioning training. These training modalities incorporate methods and strategies to improve overall performance factors, including aerobic and anaerobic profiles, strength, and power (El-Ashker et al., 2018). Therefore, the assessment and monitoring of a boxer's performance during specific training and strength conditioning are crucial components that practitioners and coaches must consider.

2.2 Boxing punch

The boxing punch is a regulated method of striking an opponent using a boxer's closed fist. The punching surface must be covered by boxing wraps and gloves. Different weight classes require the use of gloves with varying weights. For example, in amateur boxing, Elite and Youth Men weight classes from 71 to 92+ kg wear twelve-ounce gloves (approximately 340 grams) (International Boxing Association, 2022). Boxing wraps, which cover the bare fists, typically measure between 2.5 and 4.5 meters in length and must be 5.7 centimeters wide (International Boxing Association, 2022). In keeping with the rules, punches are allowed to target the area above an opponent's belt, aiming for the head or torso (Dinu & Louis, 2020a; Davis et al., 2013). Executing a boxing punch involves the activation of the entire kinematic chain of the body (Tasiopoulos et al., 2018; Blower 2012), necessitating synchronization among different body segments, including the ankle, thigh, trunk, forearm, and hand (Dinu & Louis, 2020a).

Punches can be delivered in various ways: as individual strikes or as sequences of multiple repetitive punches, incorporating different types of punches in combination, using both the lead and rear upper limbs (Davis et al., 2013). In boxing, punches are executed from two opposing stances. Right-handed boxers assume an "orthodox" boxing stance, with their right hand (the boxer's dominant hand) and right leg positioned at the rear. Conversely, left-handed boxers adopt a "southpaw" boxing stance, with the left hand (the dominant hand) and left leg in the rear position (Blower, 2012).

Regardless of whether a boxer employs an "orthodox" or "southpaw" stance, amateur boxers average approximately 188 punches per boxing bout. However, not all punches land successfully, meaning that they fail to hit the intended target. In relative values, around 86.5 % of all thrown punches miss their mark, while only 13.5 % of punches connect successfully. Regardless of the success or failure of punches, lead punches are employed more frequently than rear punches, accounting for 60.8 % and 39.2 %, respectively. Straight punches (59.6 %) are the most commonly used, followed by hooks (37.0 %) and uppercuts (3.5 %). Among straight punches, 63.0 % of them are thrown from the rear side, while hooks are performed in 85.9 % of cases from the lead side. (Davis et al., 2018)

The following sections (from 2.2.1 Lead straight punch to 2.2.6 Rear uppercut) will outline the key technical aspects, breaking down the three main boxing punches: straights, hooks, and uppercuts. Each punch will be described for both the lead and rear hand. It is important to note that each boxing punch can be executed with various technical nuances based on body type, rhythm, and range. The following descriptions present the fundamental techniques of punches targeting specifically an opponent's head, as relevant to the topic of this dissertation.

2.2.1 Lead straight punch

The lead straight punch, also known as the jab, is a straight punch executed with the non-dominant hand. It is the most fundamental and basic punch in boxing. The lead straight punch has the longest reach among punches, which is why it is commonly used to maintain a safe distance from the opponent. It is also used to disrupt the opponent's balance, limiting the opponent's ability to counterpunch. Additionally, the lead straight punch is frequently employed to initiate a punching combination – a sequence of two or more punches such as straights, hooks, and uppercuts delivered by the lead hand, rear hand, or a combination of both. (Blower, 2012)

The initial position for the lead straight punch is a boxing stance with the hands up, positioned as close as possible to one's own chin and nose. The movement begins from the feet and continues upward. First, the lead heel lifts slightly, while the front part of the foot (ball of the foot) remains in contact with the floor. This is followed by an inward twist of the ankle. Subsequently, as the hips and shoulders rotate inward, body weight is transferred from both feet to the rear foot only. The arm and lower body move simultaneously. The lead straight punch is thrown directly forward from the initial guard position. The punch is driven forward from the shoulder and accelerates towards the opponent's head (Blower, 2012). The fist and arm remain relaxed until contact with the target is made. Just before impact, the fist clenches, along with a "pulsing" contraction of the core, creating tension throughout the whole body (McGill et al., 2010). The target is typically punched at the height of the lead shoulder (adjusted based on the opponent's height). The boxer connects with the opponent with the arm fully extended. The rear hand stays in the initial position, near the chin and nose. The head, more specifically the jaw, is bent to utilize the cover provided by the lead shoulder, minimizing the risk of being counterpunched by the opponent. After making contact with the target, the lead straight punch quickly returns to the chin and nose. (Blower, 2012)

2.2.2 Rear straight punch

The rear straight punch, also known as the cross, is a straight punch executed with the dominant hand and in general is more powerful compared to lead straight punch (Smith et al., 2000; Smith, 2006; Loturco et al., 2016). Consequently, the rear straight punch is generally regarded as a more damaging punch compared to the lead straight punch (Beattie & Ruddock, 2022).

The starting position for the rear straight punch is the same as for the lead straight punch: the "boxing stance" with hands up. The rear hand follows almost the same movement pattern as the lead hand. Although it is a straight punch, the rear straight punch takes advantage of the centrifugal force generated when the back ball of the foot pushes against the floor and the torso rotates in the opposite direction. While the punch moves straight forward, the torso rotates. Similar to the lead straight punch, the rear straight punch moves directly forward, with the wrist, elbow, and shoulder unlocking and relaxing (Blower, 2012). It is propelled by a pulse from the core and pressure against the rear "ball of the foot" (proximal stiffness of the core and distal "fixed point" contracting the ground at the base of the toes) (McGill et al., 2010). The body turns, and the arm is propelled forward from the hip, then the shoulder, and into full extension. Just before contacting the target, the hand and core engage in a perfectly timed and simultaneous "pulse" when muscles of the whole body contract and the fist clenches. The rear straight punch is executed in a horizontal fashion, in line with the shoulder. The return movement to the original position should be performed as quickly as possible, similar to the lead straight punch. (Blower, 2012)

2.2.3 Lead hook

While straight punches are executed with a fully extended arm, lead and rear hooks are both performed with the arm bent at the elbow, accompanied by rotational movement around the transverse plane of the boxer's body (Beattie & Ruddock, 2022). When delivered correctly and with proper technique, the left hook is considered a damaging punch (Blower, 2012). This can be caused by a swinging motion and rotation of the entire body (Kim et al., 2018). It is commonly used as a counterpunch but also as part of an offensive tactic, depending on the way it is utilized. Since the lead hook is performed with a bent arm, it is aimed around the outside of the opponent's guard and ideally from a "blind spot" just outside the opponent's peripheral view. (Blower, 2012)

The initial position for the lead hook is the same as for other punches. The boxer adopts their preferred boxing stance (orthodox or southpaw), typically with the hands as close as possible to their own chin and nose. The movement patterns of the lower body can be identical to those used in the lead straight punch, involving extension or flexion movement from the feet upward and downward along the kinetic chain. While rotating in the transverse plane, the kinetic linkage of the whole body turns toward the target, and the lead arm accelerates around and forward at approximately a 90-degree angle at the elbow joint, although the angle may vary depending on the range. The fist is clenched just before the knuckles of glove make contact with the target (Blower, 2012). This "stiffens" the whole body at the moment of impact, allowing for greater "effective mass" (more weight is transferred through the punch and into the target) (McGill et al., 2010). The palm of the lead hand generally faces inward with the thumb on top. The weight of the body often shifts to the lead foot while throwing the hook. The head position is behind the lead shoulder, which provides protection, especially for the jaw, which is a common target. The rear hand remains close to the chin and nose. After striking the target, the lead hand quickly returns to its original position, taking the shortest possible route to avoid creating an uncovered position: the "open guard." (Blower, 2012)

2.2.4 Rear hook

The rear hook is a slower and more predictable punch compared to the lead hook. Therefore, it is typically thrown at the end of a punching combination when the opponent is in a reactive state or when a safe opportunity arises for its use (Hatmaker & Werner, 2004). Among all punches, hooks are the most common punches that result in a loss of consciousness in boxing (Cournoyer & Hoshizaki, 2019).

To execute the rear hook, the boxer assumes the same initial position as for the lead hook. The movement starts from the lower limbs, with the boxer's body weight over the lead leg. As the rear hip and shoulder turn through the center line of the boxer, the rear arm rises with an approximately 90-degree bend at the elbow joint and moves through space in an arc shape toward the target. During the punch, the wrist should maintain a straight position with the knuckles turned outward and the thumb pointing upward. The head position is the same as when throwing the lead hook, with the boxer's head covered behind the shoulder of the punching arm to avoid being counterpunched (Blower, 2012). The lead hand also provides coverage for the head, similar to the rear hand in the lead hook (Haislet, 1982). The angle at the elbow during the execution of the lead and rear hooks can vary based on the distance of the opponent (Blower, 2012).

2.2.5 Lead uppercut

Lead and rear uppercuts are mechanically different from straight punches and hooks in that they are the only punches performed in a vertical vector, while straight punches and hooks are performed in a horizontal vector (Beattie & Ruddock, 2022). Lead uppercuts can be employed at long or middle distances, but they can also serve at close distance as counterpunches. Uppercuts are often used during combination exchanges with an opponent (Blower, 2012). Because of this, the angle at the elbow joint varies according to the distance between the boxers.

The lead uppercut is performed from the same initial position as the other punches. During the movement, the lead shoulder drops, and the angle at the elbow starts to open, with the elbow dropping closer to the hip while maintaining a relaxed fist. At the same moment, the body weight shifts from both legs to the rear leg. The lead leg rotates the hip toward the opponent, with the heel rotating and pushing the front part of the foot (ball of the foot) against the floor. This helps with rotation in the hip. The lead hand is directed toward the opponent with increasing speed until contacting with the target. After the impact, the lead hand quickly returns to the chin and nose. The chin is protected behind the working shoulder, the same as in all the other punches, with the opposite fist positioned next to the chin and nose. (Blower, 2012)

2.2.6 Rear uppercut

Similar to the lead uppercut, the rear uppercut is delivered in an upright motion, where the power of the punch is generated through the extension of the lower limbs and hips (ankle, knee, and hip) (Blower, 2012).

The movement pattern of the rear uppercut is the same as in the lead uppercut, but executed on the opposite side of the boxer's body. It starts with the dropping of the rear shoulder, and at the same moment, the angle at the elbow joint starts to increase, dropping closer to the rear hip. The body weight shifts to the lead leg, while the rear heel rotates outward and around the ball of the foot, which pushes against the floor and acts as a "fixed point," enabling triple extension at the ankle, knee, and hip simultaneously. This generates significant force, which is then transferred through the stiff core into the upper limb. At the same time, the rotary moment occurs in the hips, allowing the boxer to unleash an impact force much greater than what the arm alone can produce. This force is created through the coordination and direction of the entire body linkage. The movement of the rear hand during the punch, including the return to the initial position and the cover position, is the same as in the lead uppercut. (Blower, 2012)

2.3 Parameters of training loads

To monitor and asses an athlete's performance, two measurable components are commonly used: internal and external parameters of training loads (Dudley et al., 2023; McLaren et al., 2018), which provide valuable feedback to boxers and coaches alike. Internal training load can be defined as the psychophysiological response of the human organism during exercise (Impellizzeri et al., 2019). In contrast, external training load refers to the physical work performed by the athlete (Wallace et al., 2009). Monitoring both these parameters helps in offering essential insights into an athlete's performance level, assessing how the athlete improves each parameter, and identifying the parameters of performance that the athlete should focus on.

2.3.1 Internal parameters of training loads

Commonly used internal parameters of training loads include session Ratings of Perceived Exertion (Bourdon et al., 2017), heart rate monitoring (Tabben et al., 2015), blood lactate concentration (Akubat et al., 2014), and others (Lima-Alves et al., 2022). From the practical point of view, these parameters can be accurately measured and provide valid data. However, it is always important to use relevant parameters that serve the training objective in boxing. For example, heart rate monitoring is useful when aiming to improve the boxer's physical fitness conditioning profile and monitor in which zone the boxer works. Monitoring blood lactate concentration, for example, can be used as an indicator of the boxer's physiological response to the training load (Hanon et al., 2015).

2.3.2 External parameters of training loads

External parameters commonly used during training include barbell lifting velocity (Pareja-Blanco et al., 2017a; Sánchez-Medina & González-Badillo, 2011), distance achieved during the running tests (Kempton et al., 2015), and others (Lima-Alves et al., 2022). Each parameter requires a valid measurement. For example, a linear position transducer is used to monitor lifting velocity (Wadhi et al., 2018), and global positioning systems are used to monitor the running speed and distance covered (Scott et al., 2016). These technologies were innovated with respect to their specific purpose. The linear position transducer is commonly employed to monitor external parameters during lifting loads, such as peak and mean velocity, peak and mean force, and power. Another popular monitoring device is the global positioning system, a user-friendly tool known for its portability. This system is attached to the athlete's chest, which means it cannot measure punches; instead, it measures solely distances and speeds of the chest movement in space. This is however not particularly useful for boxing, as athletes do not run around the boxing ring but rather throw punches at an opponent or a boxing bag.

Usually, both internal and external parameters of training loads are monitored during specific boxing training. Since punch force and punch velocity can be used as external parameters of training loads, it is appropriate to monitor and assess these parameters, as they closely reflect boxing performance (Beránek et al., 2020). However, there is currently no effective way to monitor punch force and punch velocity under real-life boxing conditions. The following sections (2.4 Methods of monitoring and testing punch force; 2.5 Methods of monitoring and testing punch velocity) provide further explanation of the available methods and instruments.

2.3.2.1 Velocity-based training

As mentioned above, barbell lifting velocity can be used as an external parameter during training. It is generally known that an inverse relationship exists between load and velocity, meaning that as the lifting load increases, the lifting velocity decreases (Bosquet et al., 2010; González-Badillo & Sánchez-Medina, 2011; Jukic et al., 2020b). Therefore, coaches often employ velocity-training methods during gym sessions.

Today, some of the most common training methods in strength training include traditional sets, sets to failure, and velocity-based training (Krzysztofik et al., 2019; Tufano et al., 2018). Traditional training typically involves a prescribed number of sets, repetitions, and loads, irrespective of the athlete's daily physical readiness or fatigue caused by previous training (Bartolomei et al., 2014). On the other hand, training to failure purposely induces acute neuromuscular fatigue as the athlete performs a maximum number of repetitions with a specific load until they cannot perform another one (Folland et al., 2002; Izquierdo et al., 2006). In contrast to traditional training and training to failure, velocity-based training often requires the athlete to perform an undetermined number of repetitions until movement velocity (an indirect indicator of neuromuscular fatigue) decreases to a certain extent, allowing the athlete the reach the desired fatigue within the set (González-Badillo et al., 2017; Pareja-Blanco et al., 2020; 2017b; Rodiles-Guerrero et al., 2020).

As mentioned above, velocity-based training is a method that involves using a portable device to measure velocity during strength and power exercises, such as back squats (Appleby et al., 2020), deadlifts (Jukic et al., 2020a; 2020b; 2020c), and bench press (González-Badillo & Sánchez-Medina, 2010). The portable devices used in velocity-based training allow athletes to assess their current performance by measuring lifting velocity during exercises and maintaining a desired level of fatigue, which is dependent on the training program and annual phase (off-season, pre-season, and in-season). Coaches and athletes can adjust the lifting load based on the current performance, allowing them to monitor and manipulate training variables according to individual needs and training goals.

In general, the magnitude of fatigue during a training session can be largely affected by the number of sets and repetitions for each exercise (Sánchez-Medina & González-Badillo, 2011; Pareja-Blanco et al., 2020; González-Badillo et al., 2017). Therefore, an appropriate treatment of acute training variables, such as the number of repetitions, the number of sets, and intensity, can further enhance training adaptation and improve performance.

For velocity-based training, a commonly used tool is the linear position transducer, which is attached to the barbell and provides measurements based on time-displacement outputs (peak velocity, mean velocity, peak power, mean power, etc.) of the barbell during lifting (GymAware, 2020). In addition to linear position transducers, accelerometers are also used for monitoring lifting velocity (Balsalobre-Fernández et al., 2016), However, previous studies comparing the validity of linear position transducers and accelerometers for monitoring lifting velocity across a range of exercises have shown that linear position transducers are more reliable and valid for peak velocity and mean velocity data compared to accelerometers (Banyard et al., 2017; Weakly et al., 2021).

Velocity-based training is commonly used to determine the athlete's one-repetition maximum (Jidovtseff et al., 2011; Jukic et al., 2020c; Thompson et al., 2021) and power output (Banyard et al., 2019), as well as to monitor their fatigue level and load-velocity profile (Sánchez-Medina & González-Badillo, 2011). These outputs provide instantaneous feedback on the athlete's performance and offer the option to adjust the optimal load for the current training session, such as changing the prescribed lifting load or number of repetitions within a set (Pareja-Blanco et al., 2020; Rodiles-Guerrero et al., 2020).

2.3.2.2 Punch force

Punch force is one of the two important aspects of boxing performance. The coordination of the whole body and precise technique enable the boxer to deliver powerful punches. In physics, force is represented as a vector quantity, its unit is Newton, and it can be calculated as:

$$F = m \bullet a,$$

where the symbol F represents force, m represents mass, and a represents acceleration (Zatsiorsky & Kraemer, 2006). Therefore, the body mass of the boxer influences punch force (Dunn et al., 2022). Consequently, weight classes were introduced in boxing to ensure fair conditions during bouts, as punch force differs across weight classes (Walilko et al., 2005; Pierce et al., 2006).

In addition to the boxer's weight, punch force is also influenced by the level of experience (Smith et al., 2000), calendar age, and the side from which the boxer performs the punch (Dinu et al., 2020b). Boxers with more years of training punch harder than those with less experience. According to a conducted study, boxers with an average of 11.5 years of experience achieve approximately 2,847 N and 4,800 N with lead and rear straights, respectively. In contrast, boxers with approximately 5.7 years of experience achieve an average of 2,283 N and 3,722 N, respectively. Finally, boxers with the least experience (1.5 years) achieve an average of 1,604 N and 2,281 N with lead and rear straights, respectively (Smith et al., 2000). Punch force also varies across the age of boxers and types of punches. On average, senior boxers with a mean age of 21.1 years achieve 3,158 N with rear straights, 2,999 N with rear hooks, and 3,242 N with rear uppercuts. Junior boxers with a mean age of 16.1 years achieve 1,021 N with rear straights, 544 N with rear hooks, and 700 N with rear uppercuts (Dinu et al., 2020b).

Gender also has an influence on punch force. Male boxers achieve greater punch force than female boxers with lead and rear straights. A study was conducted where male and female boxers performed punches under two different conditions (Loturco et al., 2016). First, boxers punched from a standardized position, and second, from a self-selected position. In both conditions, male boxers achieved higher results with lead and rear straights compared to female boxers. In the standardized position condition, male boxers achieved a punch force of 1,152 N and 1,331 N with lead and rear straights, respectively. In the same position, female boxers achieved 902 N and 994 N, respectively. In the self-selected position condition, male boxers achieved 1,212 N and 1,368 N with lead and rear straights, respectively; while female boxers achieved 933 N and 987 N, respectively.

However, it is important to consider that the results of different studies focused on testing punch force may vary due to differences in equipment, monitoring devices, and testing procedures. Additionally, a combination of factors mentioned above, such as boxing performance level and gender, can significantly influence punch force. This means, for example, that an experienced female boxer could punch harder compared to a male boxer with less experience. Therefore, due to the various factors that can affect punch force, it is difficult to establish a single value to accurately represent punch force for each category. It should also be noted that not all studies measured all the basic punch types, so the values listed above cannot be used to compare each punch type within each factor.

2.3.2.2 Punch velocity

Similar to punch force, punch velocity is also a critical component of boxing performance (Dinu & Louis, 2020a; Khasanshin, 2021). Like force, velocity is characterized as a vector quantity, its unit is meters per second, and it can be calculated as:

$$v = \Delta s / \Delta t,$$

where the symbol v represents velocity, Δs represents change in displacement, and Δt represents change in time (McGinnis, 2005; Lowe & Rounce, 2002). In literature, some authors also use the term speed. The main difference between velocity and speed is that speed is a scalar quantity that represents the distance traveled divided by the time taken (Lowe & Rounce, 2002):

$$v = s / t$$

In the equation, *v* represents speed, *s* represents change in distance, and *t* represents time (Holzner, 2022).

When discussing punch velocity, similar to punch force, it is difficult to provide a standardized reference value. This is because different equipment, monitoring devices, and testing procedures can yield varying results across different factors and their combinations. Therefore, obtained results may differ. Due to these variations, it is almost impossible to present results obtained during a single testing procedure with the same boxers while incorporating all the factors that can influence punch velocity, as well as punch force. These factors may include punch type, calendar age (Dinu & Louis, 2020a), the side from which the boxer performs the punch (Stanley et al., 2018), and gender (Kimm & Thiel, 2015). The following paragraphs also refer to punch speed in addition to punch velocity.

Differences in punch speed are influenced by many factors, such as punch type and the calendar age of the boxer (Dinu & Louis, 2020a). A study was conducted, showing that older boxers, with a mean age of 21.1 years, perform hooks and uppercuts faster than younger boxers, with a mean age of 16.1 years. The mean maximum punching speed for hooks was 11.2 $m.s^{-1}$ for older boxers and 8.9 $m.s^{-1}$ for younger boxers. A similar pattern was observed for uppercuts, with older boxers achieving greater mean maximum punching speed, where the velocity was 10.2 $m.s^{-1}$ for older and 7.3 $m.s^{-1}$ for younger boxers. However, both older and younger boxers achieved the same mean maximum punching speed of 8.1 $m.s^{-1}$ for rear straights.

Another study examined the peak fist velocity of lead and rear straights, lead and rear hooks, and lead and rear uppercuts (Stanley et al., 2018). On average, the peak fist velocity was greater for rear straights compared to lead straights, amounting to 6.79 $m.s^{-1}$ and 5.85 $m.s^{-1}$, respectively. Similarly, rear punches exhibited higher velocities than lead punches for uppercuts. Rear uppercuts achieved a peak fist velocity of 11.55 $m.s^{-1}$, whereas lead uppercuts achieved 10.60 $m.s^{-1}$. However, the peak fist velocity of hooks was higher for lead hooks than rear hooks, amounting to 11.95 $m.s^{-1}$ and 11.48 $m.s^{-1}$, respectively.

The side from which the boxer performs the punch also influences punch velocity. When comparing straight punches, boxers achieved greater maximum punch velocity on average with rear straights compared to lead straights, amounting to 6.64 $m.s^{-1}$ and 5.81

m.s^{-1}, respectively (López-Laval et al., 2020). Additionally, gender has an influence on punch velocity for lead and rear straight punches (Kimm & Thiel, 2015). Male boxers achieved velocities of 8.1 m.s^{-1} and 7.7 m.s^{-1} for lead and rear straights, respectively; while female boxers achieved velocities of 6.6 m.s^{-1} and 5.7 m.s^{-1}, respectively.

2.4 Methods of monitoring and testing punch force

Punch force has been investigated in several studies to determine how it is influenced by strength during different exercises (López-Laval et al., 2020; Dunn et al., 2022; Yi et al., 2022) and to explore options for monitoring and testing it (Atha et al., 1985; Smith et al., 2000; Diewald et al., 2022; Menzel & Potthast, 2021a; 2021b). The following sections describe several systems that have been proposed in literature and that are commonly using for monitoring and testing punch force.

2.4.1 Ballistic pendulum

In past, a study was conducted which utilized a cylindrical padded 7-kg pendulum with a piezoelectric force transducer to analyze the properties of the boxing punch in a heavyweight professional boxer (Atha et al., 1985). The device involved an accelerometer on hanging platters, a force transducer attached behind the target plate, a retroreflective prism of a 3-dimensional Coda Scanner, and digitizing markers for motion detection. However, due to its complexity, this device is impractical to use for monitoring punch force during specific boxing training sessions.

2.4.2 Force platforms

Among commonly used systems for monitoring and testing punch properties are devices operating based on sensor pressure, such as wall-mounted force platforms (Beranek et al., 2022, Loturco et al., 2016; 2021; Liu et al., 2022). These force platforms are equipped with a padded cover to avoid potential injuries from high impact when the fist connects with the platform. Force platforms can serve as suitable tools for monitoring and testing punch force. However, they require specific placement and are limited to particular conditions, making them unsuitable for specific boxing training activities such as bag work and sparring. A special construction is needed for testing and monitoring the upward movement of uppercuts (Beattie & Ruddock, 2022). Moreover, due to their cost and lack of portability, force platforms are better suited for laboratory testing.

2.4.3 Boxing dynamometer

The boxing dynamometer was developed as a means to determine punch force (Smith et al., 2000). The dynamometer consists of a force transducer attached to the wall, with a boxing manikin designed to simulate the head and upper body of an opponent. However, similar to wall-mounted force platforms, the practical application of the boxing dynamometer is limited due to its lack of portability and the difficulty, if not impossibility, of setting up the platform to determine the punch force for uppercuts (Beattie & Ruddock, 2022) and hooks.

2.4.4 Water-filled boxing bag

A more practical device that reflects specific boxing conditions, such as bag work, seems to be a commercial water-filled teardrop punching bag with an integrated sensor, which measures peak force of a boxing punch (Diewald et al., 2022). This system operates by detecting changes in fluid pressure within the bag. To assess its reliability and validity, a simple pendulum design with different loads was used. The water-filled bag provides reliable and valid results for peak impact force within a session. However, from a practical point of view, the standardized conditions do not fully replicate specific boxing conditions, such as boxing combinations involving repetitive punches with different punch types. Additionally, controlling and stabilizing the fluid inside the punching bag appears to pose limitations when measuring the peak force of a punch.

2.4.5 Boxing gloves with an intra-sensor system

From a practical perspective, boxing gloves with an intra-sensor system (Menzel & Potthast, 2021a; 2021b) appear to be a useful tool for monitoring and testing punch force. This is primarily because boxing gloves are essential equipment for every boxer, and the intra-sensor system eliminates the need for additional equipment, such as a force platform. The developed intra-boxing glove pressure sensor provides reliable data on punch force parameters. However, due to laboratory-controlled conditions and its relatively novelty, the boxing glove with an intra-sensor system is not currently commercially available for potential users.

2.5 Methods of monitoring and testing punch velocity

As mentioned above, specifically developed devices are commonly employed to collect external parameters of training load. For example, linear position transducers

(Banyard et al., 2017) and accelerometers (Balsalobre-Fernández et al., 2016), which have been previously validated, are used to monitor the velocity of lifting loads. These devices are convenient due to their cost-effectiveness and portability and are commonly used for performance monitoring. However, not all devices can be effectively utilized for monitoring performance in contexts for which they were not specifically designed, such as specific boxing movements. Similar to punch force, punch velocity has been examined in several studies.

2.5.1 Linear position transducer

With respect to the aforementioned, a previous study has demonstrated that the linear position transducer is a suitable measurement tool for monitoring the punch velocity of rear punches (Lambert et al., 2018). The results show moderate-to-strong measurement validity and reliability for monitoring and testing punch speed. However, the practicality of using the linear position transducer for hooks and uppercuts is questionable, as it relies on a cable for data acquisition and requires attachment to the moving object being measured. Additionally, using it during boxing training, where boxers utilize whole-body movements while maneuvering around the boxing bag or engaging with an opponent, is impractical and nearly impossible.

2.5.2 3-dimensional kinematics

Three-dimensional kinematics is commonly employed for monitoring and testing punch performance, especially punch speed (Beránek et al., 2020; Cheraghi et al., 2014; Lenetsky et al., 2020; Stanley et al., 2018; Piorkowski et al., 2011). In research, three-dimensional kinematics is considered the gold standard for its accuracy. During measuring, reflective markers are attached to the object, and high-frequency cameras record its movements. However, due to its high cost, three-dimensional kinematics is primarily used for scientific purposes rather than commercial applications (Cuesta-Vargas et al., 2010).

How was mentioned above, several of these laboratory-based devices, such as force platforms and three-dimensional kinematics, and others devices, have limitations when applied to real-life training. This limitation is further emphasized by the fact that most boxers dedicate the majority of their training time to sport-specific activities, such as sparring, heavy-bag punching, and pad punching. Therefore, monitoring day-to-day training load becomes difficult, considering the diverse range of sport-specific training methods, as well as the feasibility and practicality of the measurement methods mentioned above.

2.5.3 Accelerometers and wearable inertial sensors

Another option for measuring punch velocity is the use of accelerometers (Walilko et al., 2005; Lambert et al., 2018). Accelerometers, owing to their portability and affordability, have emerged as popular and validated technology for monitoring and testing an athlete's performance in a range of sports (Espinosa et al., 2019; Evenson, et al., 2015).

A previous study aimed to establish the concurrent validity and reliability of an accelerometer in quantifying punch speed during straight punches by untrained participants, similar to the above-mentioned linear position transducer. This study used a commercially available accelerometer called Crossbow (Lambert et al., 2018). Despite the moderate-to-strong relative validity of the tool, the Crossbow accelerometer suffers from the same limitations as the linear position transducer, so it is not practical to use for assessing punch speed. Like the linear position transducer, the Crossbow accelerometer is not wireless, which limits its usability during hooks and uppercuts, as well as other boxing conditions.

Accelerometers measure linear acceleration, but for boxing purposes, and specifically for punching, measurements of angular acceleration using a gyroscope are necessary. The combination of time-synchronized accelerometers, gyroscopes, and often magnetometers is collectively referred to as inertial measurement units. Together, these devices provide information about acceleration, angular rate, and orientation of the body in space (Aroganam et al., 2019; Tamura, 2014).

Wireless inertial measurement units have been widely used for scientific purposes (Worsey et al., 2019). In a previous study, seventeen inertial measurement unit sensors were used to investigate the differences in punching force and velocity between Elite and Junior boxers during straight punches, hooks, and uppercuts (Dinu & Louis, 2020a). Elite boxers achieved higher results in force production and punching velocity compared to Junior boxers. Additionally, punching velocity was positively correlated with punching force. Due to the wireless nature of inertial measurement unit sensors, they appear suitable for investigating external parameters of training loads, such as punch force and punch velocity during specific boxing training. However, from a practical standpoint, using seventeen inertial measurement unit sensors does not allow for instantaneous feedback on performance due to the time needed for data analysis.

In addition to providing information about force and velocity, inertial sensors can also aid in punch type recognition (Omcirk et al., 2021). In a previous study, the configuration of inertial sensors (SABELSense) was evaluated for automatic punch recognition during pad punching in boxing (Worsey et al., 2020). Study participants performed lead and rear straights, lead hooks, and lead and rear uppercuts. The study used two configurations in terms of the position of inertial sensors. The first configuration involved two sensors positioned inside boxing gloves, while the second configuration utilized three sensors. The first two sensors were placed as before, inside the boxing gloves, and the third sensor was positioned on the participant's back using a specially designed harness. The study indicated a good accuracy in punch recognition for both configurations. Therefore, the inertial sensors used in this study can be used for boxing punch recognition during specific boxing training, such as pad work or heavy bag boxing.

While the previous study evaluated the configuration of inertial measurement unit sensors for automatic punch recognition, another study aimed to examine the use of inertial measurement unit sensors with bespoke software, Boxing Punch Analyzer, for automatic classification of fatigue during boxing (Shepherd et al., 2017). The amount of fatigue during the testing protocol was assessed by analyzing the angles, accelerations, and time intervals between punches. The study involved six right-handed male Elite boxers who performed eleven five-second rounds of punching a wall-mounted boxing bag. Five seconds of inter-set rest time was provided for each boxer. Each round included sequences of lead and rear straight punches performed as fast and as hard as possible. Boxers were recorded with a 50 Hz video camera during each round for synchronization with the inertial measurement unit sensor. The main findings indicate that the tested sensor can automatically determine punches by extracting angle, acceleration, and time intervals between punches. Therefore, the inertial measurement unit sensor with the Boxing Punch Analyzer software used in this study appears to be a suitable tool for monitoring a boxer's performance, particularly the onset of fatigue during specific training sessions involving, for example, boxing with impact.

Inertial sensors, due to their wireless, portable, and small size characteristics, are suitable tools for monitoring and testing an athlete's performance (Cuesta-Vargas et al., 2010), including hand velocity and hand force of the boxer (Haff & Triplett., 2016).

However, despite the increased accessibility of this technology, boxers and coaches do not commonly utilize it for monitoring and testing the boxer's performance (Worsey et al., 2020). Given the specific conditions of boxing, such as high impact acceleration, humidity, and temperature effects, as well as wireless connectivity problems due to multiple body rotations and the contact nature of the sport, the placement and the shape of the sensors must avoid potential injury to boxers during punching. Additionally, the sensors must not lose their functionality due to high impact forces during punching and defensive maneuvers of boxers (Worsey et al., 2019). In response to these specific conditions, the commercial market offers sensors known as punch trackers (Omcirk et al., 2021; Omcirk et al., 2023). However, before their use in scientific or real-life training settings, the validity of these punch trackers needs to be established.

2.6 Testing boxing-specific performance

In addition to specific boxing training, boxers also incorporate strength and conditioning training to improve the specific abilities required for boxing performance. Since a boxing punch is a complex whole-body movement, it is important to include exercises that reflect this specific movement.

2.6.1 Bench press

The bench press is considered one of the most popular exercises in the weight room due to its complexity, and it is commonly utilized in various sports disciplines to enhance athletes' strength abilities and assess their strength levels (Jidovtseff et al., 2011). Given that the bench press primarily engages the upper body, it may appear to be a suitable test for boxers, considering its similar movement pattern to the straight punch (López-Laval et al., 2020).

A previous study aimed to determine the association between relative intensity during the bench press, using different percentages of one-repetition maximum, and the peak velocity of hand movement achieved during lead and rear straight punches in professional boxers (López-Laval et al., 2020).. Each boxer performed three repetitions of lead and rear straight punches with maximum effort (as fast as possible) on a heavy boxing bag. The maximum velocity of the hand movement was measured during these punches. To assess maximum bench press velocity, boxers performed a one-repetition maximum test, progressively increasing the load from an estimated 50 % of one-repetition maximum until reaching the highest possible load.

This study found a relationship between the achieved maximum velocity in the bench press, ranging from 30 % to 80 % of one-repetition maximum, and the peak velocity of straight punches, specifically the rear straight punch. The strongest relationship was observed at 80 % of one-repetition maximum ($r = 0.815$), while the weakest relationship was at 30 % of one-repetition maximum ($r = 0.644$), both for the rear straight punch. However, the achieved peak velocity of the lead straight punch did not correlate with maximum velocity at any of the bench press intensities. This difference in correlation might be attributed to the technical aspects of each movement, as the rear straight punch is more similar to the bench press than the lead straight punch (López-Laval et al., 2020). Therefore, if coaches and boxers aim to enhance hand peak velocity, it seems appropriate to include the bench press in strength and conditioning training, particularly using a higher percentage of one-repetition maximum.

2.6.2 Bench press throw

Another variation of the bench press is the bench press throw. Like the bench press, the bench press throw involves a movement pattern resembling straight punches. During a bench press throw, athletes perform the concentric phase as explosively as possible, extending the upper limbs fully, followed by throwing the barbell as high as possible (Loturco et al., 2016; Bartolomei et al., 2018). Since the bench press throw primarily engages the upper body, it can be practical for monitoring and assessing upper-body ballistic abilities (Krzysztofik et al., 2021).

A previous study (Loturco et al., 2016) aimed to determine the association between the impact force of lead and rear straight punches and the mean propulsive power in strength-power exercises, such as the bench press throw. To assess the impact force of straight punches, each boxer (nine male boxers and six female boxers) performed twelve punches on a wall-mounted force plate. This included three lead and three rear straight punches from the standardized position and three lead and three rear straight punches from a self-selected position. In the standardized position, boxers performed punches that allowed for a full extension of the dominant arm upon contact with the force plate, while in the self-selected position, the boxers adopted each their preferred position. To determine the mean propulsive power during the bench press throw, each boxer performed as fast as possible three repetitions at 30 % of their individual body mass, progressively increasing the load by 5 % of their individual body mass until a decrease in mean propulsive power was observed. The maximum mean propulsive power achieved during bench press throw was used for data analysis.

This study did not find a significant difference in the 95 % confidence interval correlation coefficient between male and female boxers, so only the group results were reported. A strong association was observed between the impact forces of each position for lead and rear straight punches and the mean propulsive power in bench press throws. The highest association was observed for self-selected rear straight punches ($r = 0.78$), while the lowest association was observed for standardized position lead straight punches ($r = 0.70$). (Loturco et al., 2016)

As mentioned above, the bench press throw exhibits a movement pattern similar to straight punches. Therefore, the bench press throw appears to be a suitable specific-movement exercise for boxers to target upper-body strength, which is associated with the impact forces of lead and rear straight punches.

2.6.3 Medicine ball throw

The medicine ball is a popular piece of equipment used in strength and conditioning training (Stockbrugger & Haennel, 2001). It has various variations, such as the medicine ball punch (Ruddock et al., 2016), two-hand overhead throw, two-hand side-to-side throw, power drop, and others (Haff & Triplett, 2016). Due to its portability and minimum equipment requirements, exercises with the medicine ball can be suitable as field tests, especially when the variations reflect specific performance in sport disciplines. For boxing-specific performance, exercises with the medicine ball that mimic the movement pattern of a boxing punch, such as the medicine ball throw, can be practical (Ruddock et al., 2016).

A previous study aimed to determine the validity and reliability of the seated medicine ball throw using 1.5 kg and 3.0 kg medicine balls (Harris et al., 2011). To assess the validity of the achieved horizontal distance in the seated medicine ball throw, the explosive push-up was used as the criterion, specifically its peak vertical force. The study found moderate validity ($r = 0.641$ and $r = 0.614$) for the 1.5 kg and 3.0 kg variations, respectively. Additionally, both variations showed high reliability ($r \geq 0.958$). Therefore, the seated medicine ball throw appears to be a suitable field test for assessing upper-body power, particularly due to its reliability.

However, it is important to consider the technique execution of the medicine ball throw. Degrees of freedom in execution may influence the results, when factors such as the angle and direction of the throw can influence the achieved horizontal distance.

2.6.4 Landmine punch throw

The landmine punch throw is a suitable exercise commonly used as a punching-specific test due to its ability to produce high velocities with a movement pattern similar to a boxing punch, especially when performed with the rear hand. To track the velocity obtained during the landmine punch throw, a linear position transducer (GymAware) can be used, which has been previously validated for assessing peak velocity during strength and power exercises. (Ruddock et al., 2018)

The exercise requires a three-dimensional moveable attachment on the floor, an Olympic barbell (20 kg), and additional loads that can be added to the barbell, based on the boxer's performance. One end of the barbell is fixed to the three-dimensional moveable attachment, while the other end is held by the boxer as close to their rear shoulder as possible. The cable of the linear position transducer is attached to the higher end of the body of the barbell, where it meets the barbell's rotating end.

The boxer assumes one of the two aforementioned boxing stances with slightly flexed lower limbs. The lead hand is close to the chin, and the rear hand grips one edge of the barbell near the rear shoulder. The movement itself is similar to a rear straight punch, involving shifting the body mass to the rear leg, simultaneous whole-body rotation in the direction of the barbell, followed by rear leg extension, trunk rotation, upper limb extension, and a ballistic throw of the barbell. The entire movement is performed as quickly as possible.

Due to the unilateral nature of the landmine punch throw and its similarity to the movement pattern of a boxing punch, it appears to be a practical tool for monitoring and testing specific punching performance. The ability to perform the exercise with both the dominant and non-dominant hand allows boxers and coaches to use similar movement patterns during training sessions and explore potential asymmetry between the limbs, aiding in identifying areas for improvement. However, there is currently no evidence available on the landmine punch throw (Uthoff et al., 2023).

3 Importance of punch type recognition

Practicing boxing punch technique and performing shadow boxing are essential and suitable parts of boxing training, regardless a boxer's performance level. Specifically, shadow boxing is commonly used during the warm-up and as a means to increase the number of punch repetitions performed to improve punching technique. Furthermore, shadow boxing is easy to implement in training as it does not require any equipment or an opponent. Therefore, boxers have more opportunity and freedom to perform individual punches and different punch sequences without any interference such as counter-punches from an opponent that could impair their ability to perform multiple punches with sound technique.

During shadow boxing, boxers perform a high number of single punches and also sequences of multiple punches. Although these can be prescribed ahead of time, shadow boxing often results in a boxer "going with the flow" and performing different punch sequences as they see fit. In these cases, the boxer is increasing their training load arbitrarily, without knowing what exactly the have done. Indeed, heart rate and perceived exertion can be monitored, but he amount of punches and the recognition of specific punch types could provide concrete feedback about training volume of load during shadow boxing.

It is true that video recording can be useful for monitoring a detecting punches after training, but such video analyses need a lot of time and only provide the results after the boxing session. Therefore, it would be suitable to use a tool which provide instantaneous feedback about detected punches thrown during shadow boxing, especially, when punches are performed in sequence.

When this study was conducted, wearable technology started to become an increasingly popular tool for monitoring performance in real-life conditions. For example, different wearable devices could provide runners with information about their distance, stride length, stride frequency, and the like. With this data, runners could quantify certain aspects of their training, but the same could not be done for punching until punch trackers were innovated for specific boxing movements.

Punch trackers generally have a accelerometers and gyroscopes, which are essential for detecting and recognizing punch types. Due to the high movement speeds and movements in all three axes, punch trackers have their own algorithms which theoretically should be able to detect punches and recognize which punch was thrown. However, these internal properties are not publicly available and users must trust that the manufacturers created valid tools for detecting and recognizing punches. As a coach and a scientist, this was unsatisfactory, and there were no studies that had aimed to determine the validity of commercially available punch trackers during shadow boxing.

Therefore, the following study aimed to compare four commercially available punch trackers (Corner, Everlast, Hykso, and StrikeTec) to determine how well they could recognize and detect punches during shadow boxing. Each of those punch trackers are advertised for boxers regardless of their performance level, but it is possible that different punch styles or techniques may be recognized better or worse by each punch tracker's own algorithms. Therefore, ten participants with experience in combat sports involving punching and eleven participants without any of experience with combat sports performed three standardized round of shadow boxing, including single-punches, double-punches, and triple-punches sequences to determine whether training level could impact the validity of these devices. Each shadow boxing included a set of fifty-four punches within straight punches, hooks, and uppercuts for lead and rear hand to ensure that different punches and different combinations that should show up in a real shadow boxing bout would be included in the study.

In 2021, the following text presented within Chapter 4 was published as a manuscript in the journal *Sensors*. However, the formatting has been changed from the original submitted manuscript to allow for continuity throughout the entire dissertation.

The text, the information in the tables, graphs, and figures have not been altered in any way. Only the citation format has been modified. However, the actual references have not been altered and they are listed at the end of this dissertation.

4 Study 1: Punch trackers: correct recognition depends on punchy type and training experience

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Supplementary materials: Attached as Appendix 8

4.1 Abstract

To determine the ability of different punch trackers (Corner, Everlast, and Hykso) to recognize specific punch types (lead and rear straight punches, lead and straight hooks, and lead and rear uppercuts) thrown by trained and (n = 10) and untrained (n = 11), subjects performed different punch combinations, and punch tracker data were compared to data from video recordings to determine how well each punch tracker recognized the punches that were actually thrown. Descriptive statistics and multilevel modelling were used to analyze the data. The Corner, Everlast, and Hykso detected punches more accurately in trained than untrained, evidenced by a lower percentage error in trained ($p = 0.007$). The Corner, Everlast, and Hykso detected straight punches better than uppercuts and hooks, with a lower percentage error for straight punches ($p < 0.001$). The recognition of punches with Corner and Hykso depended on punch order, with earlier punches in a sequence recognized better. The same may or may not have occurred with Everlast, but Everlast does not allow for data to be exported, meaning the order of individual punches could not be analyzed. The Corner and Hykso both seem to be viable options for tracking punch count and punch type in trained and untrained.

4.2 Introduction

Boxing is not only a popular combat sport with a long tradition, but it has recently become a popular fitness trend as well (Kravitz et al., 2003), with everyday people participating in boxing- related fitness classes hoping to improve their aerobic capacity, reduce their body fat percentage, etc. As this type of training reduces obesity (Cheema et al., 2015), increases cardiovascular health (Buchheit & Laursen, 2013; Cheema et al., 2015), and improves aerobic capacity (Milanović et al., 2015), it is no surprise that people seek to participate in this type of high-intensity training. However, as with most types of training, the volume and intensity of training are two of the main factors to consider when designing and implementing a training program. In traditional exercises, such a strength training, it is easy to prescribe a set number of repetitions with a specific load. However, the non-structured, repetitive, and highly dynamic nature of punching makes it difficult to prescribe or quantify training loads. Therefore, it would be advantageous to use technology that could provide objective data to quantify training volume while punching.

Among the available technology today, accelerometers can be used to detect punch type and provide data regarding punch force, velocity, power, and other measures that can help quantify punching training structure, volume, and intensity (Laursen & Buchheit, 2019; Shepherd et al., 2017; Worsey et al., 2020). Other technologies available include high-frame-rate video capture (Ishac & Eager, 2021). Although accelerometers have been tested during punching (Worsey et al., 2020; Gatt et al., 2020), they have primarily included custom-made devices and algorithms that likely are not used by commercial users. Furthermore, the data collected in those studies are unique to specific audiences (e.g., for scoring and judging strikes, wrist angles, and other variables that everyday users likely are not interested in). Additionally, accelerometers that are invented specifically for the purpose of collecting punching data provide post-workout summaries, known as punch trackers, can even provide instantaneous feedback (Gatt et al., 2020; Worsey et al., 2019), which has been shown to play a role in maximizing acute performance (Randell et al., 2011) and increasing motivation (Weakley et al., 2019a, 2019b; Rupp et al., 2016). Although these devices are interesting, and the data they provide could be useful, there is a lack of published data to support their validity, likely due to the novelty of the devices.

Although not publicly available, it can be assumed that the algorithms of these punch trackers slightly differ between manufacturers (Aroganam et al., 2019). Furthermore, since the resultant data are based on accelerometry, it is possible that punches thrown with slightly different techniques or trajectories may not be recognized by the punch trackers, reducing their accuracy in terms of quantifying training volume or providing objective feedback. Along these lines, it is possible that the same punches thrown by untrained punchers with less technically correct movement may not be recognized as well as in trained punchers who have better and possibly more consistent punch techniques, especially for more complex movements that require greater coordination (e.g., hooks versus jabs) (Piorkowski et al., 2011). Although consumers use these punch trackers during training, their validity has not been assessed in an independent laboratory, which could provide additional information in terms of their ability to function well in real-world settings. Therefore, the purpose of this study was to compare four commercially available punch trackers to determine how well they could recognize specific types of boxing punches thrown by trained punchers and untrained punchers during shadow boxing. This study hypothesized that (I) the punch trackers would better register the total number of punches thrown by trained punchers compared to untrained punchers; (II) simple punches (lead and rear straights) would be detected with higher accuracy than more complex punches, such as lead and rear hooks and uppercuts; and (III) punch recognition would decrease throughout a consecutive sequence due to the hands not "resetting" after each punch, which may not align with the punch algorithms within the devices.

4.3 Methods

4.3.1 Subjects

Twenty-one healthy males, including 10 trained punchers (TR) (28.1 ± 5.5 y, 83 ± 11 kg, 178.2 ± 9.2 cm) and 11 untrained punchers (UNTR) (27.3 ± 6.1 y, 84.5 ± 12.5 kg, 182.6 ± 7.4 cm) volunteered for this study. The TR participants had been formally taught how to execute different types of punches, were experienced with combat sports involving punching for at least one year, and had completed at least one competition fight in any discipline that involved punching (e.g., boxing, mixed martial arts, and kickboxing). The UNTR participants had never been formally taught how to execute different punch techniques and had not participated in any formal fights. All participants had no recent injuries that would affect or be exacerbated by shadow boxing and were allowed to adopt their preferred stance (orthodox or southpaw). All participants provided written informed consent for the study protocols (approval 127/2019).

4.3.2 Design

Participants reported to the laboratory, and all data were collected during a single session. During this session, each participant was familiarized with the testing procedures and completed a standardized series of shadow boxing combinations (i.e., punching the air) with four commercially available punch trackers. All punches were recorded with a video camera (the recordings of which were considered as the gold-standard for punch recognition), and the number of each punch type that actually occurred was later compared to the number of punches provided by each of the punch trackers. In addition to assessing the validity of the punch trackers to recognize the correct punch types in all of the participants, a sub-group analysis compared TR and UNTR to determine if training status, and an assumed better technique in TR, affected the validity of the punch trackers.

4.4 Methodology

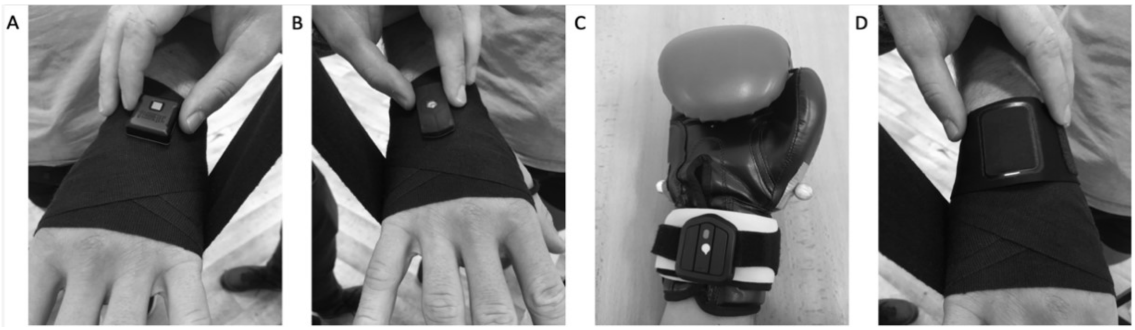
4.4.1 Warm-up and familiarization

Following a standard dynamic warm-up, each participant was provided with the same verbal and physical instructions for each punch type and performed 3 min of technique practice. During this time, the participant stood behind the researcher and performed the same punches as modelled by the researcher (i.e., in the same third-person point of view as the video instructions during the experimental period, explained below). The participants received feedback if the punch was performed incorrectly, and were instructed on how they should adjust their technique so that the punch would be correctly executed. This level of instruction is similar to what a beginner might receive in a group exercise class, increasing ecological validity of the testing procedures.

4.4.2 Validation testing

All testing was performed in the same laboratory with standard 10-ounce boxing gloves and 2.5-m boxing hand wraps that were used to secure the accelerometers according to each manufacturer's guidelines. The four commercially available punch trackers included models manufactured by Corner (Corner Boxing Trackers, Corner Wearables Ltd., Manchester, UK, v1.3.1(CPT)), Everlast (Boxing-Sensor System—PiQ Robot™Blue, Everlast Worldwide Inc., Moberly, MO, USA, v2.4.1(EPT)), Hykso (Hykso Wearable Punch Trackers, Hykso Inc., Costa Mesa, CA, USA., v1.6(HPT)), and StrikeTec (StrikeTec Boxing Sensors, StrikeTec, Dallas, TX, USA, v1.4.4(SPT)). The CPT, HPT, and SPT were attached on the wrist on the surface of the wrist extensors, and the EPT was attached on the wrist on the surface of the wrist flexors. The HPT and SPT were inserted directly on top of the wrist, under the 2.5 meters hand wraps, and under the gloves, while the CPT and EPT were inserted into their respective wristbands that were sold with the accelerometers; the Corner was then covered by the 2.5 meters hand wraps and gloves, and the EPT was attached on the wrist (Figure 1). Each punch tracker was used as a pair, attached to the lead and rear hand.

Figure 1. Punch tracker placement



A) the StrikeTec punch tracker inserted directly on top of the wrist, under 2.5 m hand wraps, and under the gloves; (**B**) the Hykso punch tracker inserted directly on top of the wrist, under 2.5 m hand wraps, and under the boxing gloves; (**C**) the Everlast punch tracker attached on the wrist on the surface of the wrist flexors on boxing gloves in their respective wristbands; and (**D**) the Corner punch tracker inserted directly on top of the wrist, under 2.5 m hand wraps, and under gloves, in their respective wristbands.

Since some of the punch trackers have the same recommended placement, they were not all used at the same time, resulting in three separate but identical rounds of shadow boxing. To avoid an potentional order effect, the order of the accelerometers was randomized in a counter-balanced fashion among the participants. Each round of shadow boxing included a standard set of 54 punches that included lead straight punches (LS), rear straight punches (RS), lead hooks (LH), rear hooks (RH), lead uppercuts (LUC), and rear uppercuts (RUC). To avoid any order effect for punch type within any possible punch combination, the punches were split into series that included a pyramid of six single-punches, six double-punch sequences, six triple-punch sequences, six double-punch sequences, and six single-punches (54 total punches per round). The sequences of punch combinations were randomized, but the number of punch types per sequence was constant for every participant, and every participant performed the same set of punches in the same sequence (see Table 1 for an example).

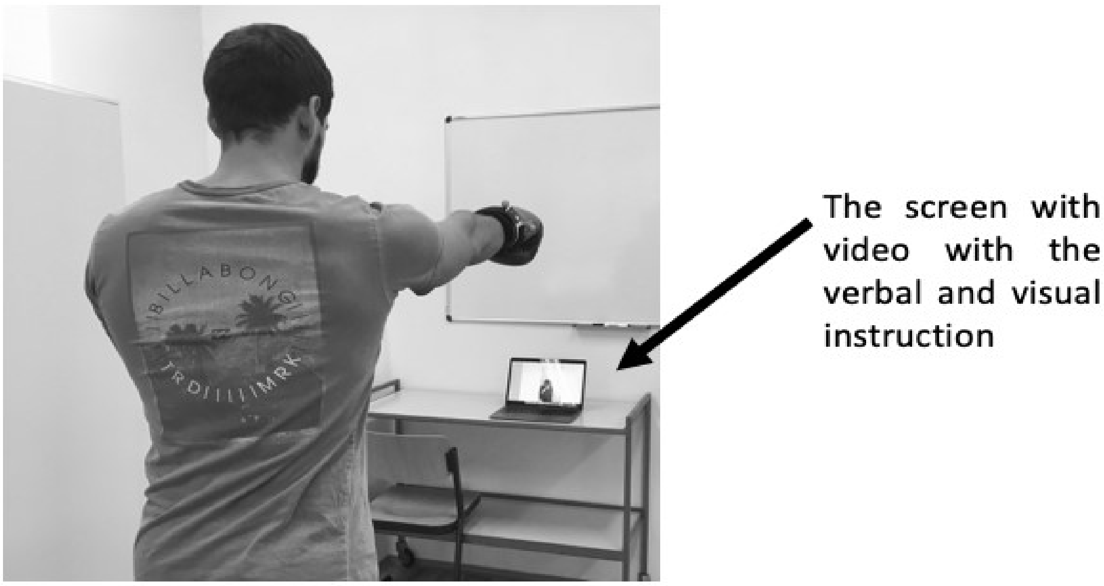
Table 1. An example of 1 round of shadow boxing.

Order	Single	Order	Double	Order	Triple	Order	Double	Order	Single
1	LS	7–8	LS+RS	19–21	LS+RS+LH	37–38	LH+RS	49	RS
2	RS	9–10	RS+LH	22–24	RS+LS+RUC	39–40	RUC+LUC	50	LUC
3	RH	11–12	RH+LUC	25–27	LUC+RH+LS	41–42	LS+RH	51	LH
4	LH	13–14	RUC+LS	28–30	RH+LH+RH	43–44	RUC+LH	52	LS
5	LUC	15–16	LUC+RH	31–33	LH+RUC+LUC	45–46	RH+RUC	53	RUC
6	RUC	17–18	LH+RUC	34–36	RUC+LUC+RS	47–48	RS+LS	54	RH

Lead straight punch (LS), rear straight punch (RS), lead hook (LH), rear hook (RH), lead uppercut (LUC), and rear uppercut (RUC).

Participants performed all of the punches as fast and hard as possible (with maximal effort). Before each punch series, each participants was shown an identical video with the same verbal and visual instructions. The video was shown on a laptop and included a member of research team performing the upcoming punches using a third-person view from the rear, as this set-up seemed best for the UNTR to mimic during pilot testing (Figure 2). There was 10 s of rest between each combination.

Figure 2. Instructional video



The participant stood in front of the screen with the video with verbal and visual instructions.

After completing a round of 54 punches, 5 min of rest was provided, and the next punch tracker was placed on the participant. The same procedures occurred for the second round (i.e., second punch tracker), followed by 5 min of rest, and then the final round. The order of PTs was randomized for each round, but since the EPT was attached on the opposite side of wrist, it was randomly placed during the first, second, or final round, meaning that one of the three rounds included the EPT and one of the other punch trackers simultaneously.

4.4.3 Data acquisition

All punches were video-recorded on a tablet from the rear at a 45-degree angle, allowing the main investigator to clearly analyze the exact number of punches for each type. Mainly in the UNTR group, it was possible that a participant accidentally threw the wrong type of punch in a specific series. For example, instead of performing an RH, they performed an RUC. In these cases, the actual punch type that was thrown (assessed via video) was recorded, as that was the punch type to be recognized by the punch tracker. Data from CPT and HPT were transmitted via Bluetooth to a laptop, and their respective data were exported in a csv file and converted to Microsoft Excel for future analysis. Data from EPT and SPT were rewritten from their respective mobile applications (EPT-Everlast and PIQ; SPT-StrikeTec Boxing), because they do not allow for direct export to a csv file. Thus, the data were manually imported to Microsoft Excel. Due to technical failures and incomplete/missing data sets for some participants, data from all 21 participants were not always included in the final analyses. Therefore, the final participants counts with full data sets were as follows: HPT (n = 21); CPT (n = 20); EPT (n = 18); and SPT (n = 0). The information provided by each punch tracker is shown in Table 2. As a note, the SPT would only register a few "random" punches for a select few participants (a mixture of TR and UNTR). Therefore, it is possible that the devices were faulty, or that they were not operated correctly, but it is also possible that the SPT simply did not work as expected. It is not known exactly what the problem was, but future research should determine the efficacy of SPT and whether another set of SPT performs similarly.

Table 2. Information provided by each punch tracker (PT).

PT	PT Placement	Manufacturer's Wraps	Strike Speed	Intensity/Power Output	Strike Count	Strike Type	Export Function*
Hykso	Wrist (inside glove)	No	Yes (maximum)	Intensity score	Yes	Yes	Yes
Corner	Wrist (inside glove)	Yes	Yes (unspecified)	Power G	Yes	Yes	Yes
StrikeTec	Wrist (inside glove)	No	Yes (unspecified)	Power (LBS/F)	Yes	Yes	No
Everlast PIQ	Wrist (outside glove)	Yes	Yes (average)	G-Force, avg. PIQScore, max. retraction	Yes	Yes	No

* The StrikeTec shows individual punch data, but they cannot be exported for external use. The Everlast PIQ neither shows the data for individual punches nor allows the workout summary to be exported for external use. Other information, such as the sampling frequency, is not provided, and the companies did not respond to the request for any extra information.

4.4.4 Statistical analyses

To assess the validity of the punch trackers to determine the total punch count during shadow boxing, percentage errors between the recorded (by the tracker) and true (as determined from video recording) number of punches were calculated for each round of shadow boxing. Based on this, mean percentage errors (MPE) and mean absolute percentage errors (MAPE) with their 95% confidence intervals were calculated for all participants combined and separately for TR and UNTR subgroups. Furthermore, equivalence testing was carried out by the two one-sided tests (TOST) method with $\alpha = 0.05$. The equivalence zone was defined as within ±10% of the true punch count. To assess the effect of training and of punch type on the log-transformed percentage errors, linear mixed effect models were fitted using lme4 (version 1.1-20) and lmerTest (version 3.1-0) packages in R, version 3.5.2 (The R Foundation for Statistical Computing, Vienna, Austria). To determine the effect of specific punch types on the log-transformed percentage errors, post hoc pairwise comparison using general linear hypotheses testing was performed with the multcomp (version 1.4-8) package in R.

To assess the validity of the punch trackers to recognize individual punch types, sensitivity and specificity were calculated for each punch type. Sensitivity was calculated as the ratio of correctly recognized (true positive) punches and all punches of a given type; specificity was calculated as the ratio of punches correctly recognized as not being of a given type (true negative) and all punches not being of a given type. Furthermore, logistic regression with mixed effects was used to assess the effect of context (i.e., order of the punch within a sequence, early vs. late in the round) on the ability of the punch trackers to correctly identify and recognize individual punches. The data presented in this study are available in supplementary materials.

4.5 Results

The total punch counts for each punch type and each punch tracker are shown in Table 3. The punches in the video recordings were all able to be identified as a specific punch type by the researcher, indicating that the movement pattern of the subject's hands matched what would be expected for such a punch type. Therefore, the researcher judged that all punches were performed within the expected movement patterns, but it was possible that subjects performed an LH instead of an LUC (for example). In these cases, the LH was the actual punch thrown, which was recognized by the punch tracker. The results of MPE, MAPE and TOST for CPT, EPT and HPT for all participants and each group (TR and UNTR) are shown in Table 4. The linear mixed-effects model indicated that the percentage error was significantly affected by punch type ($p < 0.001$) and training experience ($p = 0.007$). Specifically, the post hoc analysis revealed that the percentage error was lower for straight punches (lead and rear) compared to hooks and uppercuts ($p < 0.001$) for all three punch trackers (Table 5).

Table 3. Mean and standard deviation of shadow boxing punches that were recorded by each punch tracker and the actual punches that were thrown.

	HPT (TR, n = 10; UNTR, n = 11)		CPT (TR, n = 10; UNTR, n = 10)		EPT (TR, n = 7; UNTR, n = 11)		SPT (TR, n = 6; UNTR, n = 11)	
	Tracker	**Actual**	**Tracker**	**Actual**	**Tracker**	**Actual**	**Tracker**	**Actual**
Total TR	53.2 ± 2.8	53.9 ± 0.3	55.6 ± 4.8	53.9 ± 0.3	57.3 ± 8.5	54.0 ± 0.0	12.7 ± 8.0	54.0 ± 0.0
Total UNTR	46.5 ± 7.4	54.0 ± 0.0	52.7 ± 2.2	53.8 ± 0.6	45.8 ± 7.0	54.0 ± 0.3	9.6 ± 10.3	54.0 ± 0.0
LS TR	12.5 ± 2.0	9.2 ± 0.6	11.1 ± 2.8	9.1 ± 0.3	11.7 ± 5.1	9.3 ± 0.7	5.3 ± 2.4	9.0 ± 0.0
LS UNTR	10.6 ± 2.1	8.8 ± 0.7	12.0 ± 4.1	8.9 ± 0.3	12.5 ± 4.9	8.9 ± 0.5	3.7 ± 3.9	9.0 ± 0.4
RS TR	13.5 ± 4.5	8.8 ± 0.6	13.3 ± 4.1	8.9 ± 0.3	10.4 ± 2.5	8.7 ± 0.7	5.5 ± 4.2	9.0 ± 0.0
RS UNTR	10.5 ± 1.9	9.1 ± 0.3	11.7 ± 2.9	9.1 ± 0.3	9.6 ± 1.8	9.2 ± 0.6	5.8 ± 6.7	9.0 ± 0.4
LH TR	9.1 ± 2.5	9.4 ± 0.7	8.6 ± 3.4	8.8 ± 0.6	8.0 ± 2.7	9.3 ± 0.5	0.5 ± 0.8	9.2 ± 0.4
LH UNTR	4.9 ± 2.1	9.1 ± 0.3	7.0 ± 3.7	9.3 ± 1.2	4.2 ± 3.9	9.6 ± 1.2	0.1 ± 0.3	9.5 ± 1.2
RH TR	6.4 ± 1.7	8.8 ± 0.4	5.3 ± 3.4	9.1 ± 0.8	8.3 ± 7.7	8.9 ± 0.4	1.3 ± 2.0	8.8 ± 0.4
RH UNTR	5.9 ± 2.7	9.4 ± 0.8	4.4 ± 2.5	9.0 ± 0.4	8.6 ± 3.1	8.9 ± 0.8	0.0 ± 0.0	8.7 ± 0.6
LUC TR	4.7 ± 2.1	8.0 ± 0.6	7.0 ± 1.7	7.9 ± 0.5	6.7 ± 3.3	7.7 ± 0.5	0.0 ± 0.0	7.8 ± 0.4
LUC UNTR	6.0 ± 2.9	8.3 ± 0.8	6.9 ± 2.8	8.2 ± 0.7	5.9 ± 3.5	8.5 ± 1.2	0.0 ± 0.0	8.5 ± 1.2
RUC TR	7.0 ± 3.6	9.7 ± 0.6	9.3 ± 4.0	10.2 ± 0.8	9.7 ± 5.0	10.1 ± 0.4	0.0 ± 0.0	10.2 ± 0.4
RUC UNTR	8.6 ± 1.2	9.4 ± 0.6	9.9 ± 2.6	9.4 ± 1.2	5.2 ± 3.8	9.1 ± 1.5	0.0 ± 0.0	9.3 ± 1.5

Hykso (HPT), Corner (CPT), Everlast (EPT), and StrikeTec (SPT) and the actual number of punches thrown for trained participants (TR) and trained participants (UNTR). The standard set for each punch tracker (TR and UNTR) consisted of 54 punches; lead straight (LS (n = 9)), rear straight (RS (n = 9)), lead hook (LH (n = 9)), rear hook (RH (n = 9)), lead uppercut (LUC (n = 8)), and rear uppercut (RUC (n = 10)). For example, if a subject was supposed to perform an RH, RS, RUC, but they instead performed RH, RS, RH, the "RH, RS, RH" is what was actually thrown, so that should have been what the punch trackers recognized.

Table 4. Summary results for each punch tracker across all participants, trained participants, and untrained participants.

	MPE (95% Confidence Limits)	MAPE (95% Confidence Limits)	TOST *p*-Value
	All participants		
CORNER	0.005 (−0.080 to 0.090)	0.031 (0.000 to 0.207)	0.014
EVERLAST	−0.058 (−0.159 to 0.044)	0.127 (0.000 to 0.405)	0.208
HYKSO	−0.080 (−0.153 to −0.007)	0.095 (0.000 to 0.343)	0.296
	Trained participants		
CORNER	0.031 (−0.096 to 0.158)	0.043 (0.000 to 0.236)	0.142
EVERLAST	0.065 (−0.093 to 0.223)	0.066 (0.000 to 0.381)	0.332
HYKSO	−0.016 (−0.136 to 0.104)	0.043 (0.000 to 0.090)	0.086
	Untrained participants		
CORNER	−0.020 (−0.134 to 0.093)	0.020 (0.000 to 0.113)	0.084
EVERLAST	−0.136 (−0.266 to −0.006)	0.165 (0.005 to 0.338)	0.706
HYKSO	−0.138 (−0.023 to −0.054)	0.143 (0.000 to 0.347)	0.813

Mean percentage error (MPE) and mean absolute percentage error (MAPE) with their 95% confidence limits, and equivalence test (TOST p-value), are shown. The advisable values for MPE and MAPE are close to zero.

Table 5. Pairwise comparison of the effect of the punch type.

Punch Types Compared	ß	*p*-Value	Punch Types Compared	ß	*p*-Value	Punch Types Compared	ß	*p*-Value
LS-RS	−0.000	1	LH-LS	−0.270	<0.001	RH-LH	−0.045	0.859
LH-RS	−0.270	<0.001	LUC-LS	−0.259	<0.001	RUC-LH	0.049	0.805
LUC-RS	−0.260	<0.001	RH-LS	−0.315	<0.001	RH-LUC	−0.056	0.710
RH-RS	−0.315	<0.001	RUC-LS	−0.221	<0.001	RUC-LUC	0.038	0.922
RUC-RS	−0.221	<0.001	LUC-LH	0.011	1	RUC-RH	0.094	0.151

Lead straight (LS), rear straight (RS), lead hook (LH), rear hook (RH), lead uppercut (LUC) and rear uppercut (RUC) on percentage error of the three punch trackers combined (Corner, Hykso, Everlast). ß expresses a difference between percentage errors achieved by the two punch types. For example, in the second row (LH-RS), ß-value of −0.270 means that the percentage error achieved by RS is lower by 0.270 compared to the percentage error achieved by LH.

The sensitivity and specificity for CPT and HPT for recognizing individual punches (LS, RS, LH, RH, LUC and RUC) are present in Table 6. The logistic regression with mixed effects indicated that there was a significant negative effect of the order within a sequence ($p < 0.001$ for CPT and $p < 0.001$ for HPT) and positive effect of the position within a round ($p = 0.024$ for CPT and $p = 0.003$ for HPT). In other words, the earlier within a sequence and the later within a round the punch was thrown, the better it was recognized.

Table 6. Sensitivity and specificity of Corner and Hykso punch trackers to correctly recognize individual punches.

	Corner		Hykso	
Punch	**Sensitivity**	**Specificity**	**Sensitivity**	**Specificity**
STRAIGHT LEAD	0.833	0.917	0.958	0.935
STRAIGHT REAR	0.911	0.895	0.947	0.927
LEAD HOOK	0.648	0.958	0.521	0.958
REAR HOOK	0.538	0.991	0.497	0.960
LEAD UPPERCUT	0.741	0.977	0.560	0.976
REAR UPPERCUT	0.783	0.956	0.665	0.972

Using the straight lead as an example, sensitivity is the proportion of straight lead punches that were correctly recognized as such, and specificity is the proportion of non-straight lead punches that are recognized as non-straight lead punches (but not necessarily recognized correctly). Sensitivity and specificity values as close as possible to one are desired.

4.6 Discussion

The main findings are that (I) the CPT, EPT, and HPT all detected punches with more accuracy in TR than UNTR participants; (II) the CPT, EPT, and HPT were all better at detecting straight punches compared to uppercuts and hooks; and (III) the successful recognition of punches with CPT and HPT depended on the order of boxing punches, with earlier punches in a sequence being recognized better. The same may or may not have occurred with the EPT, but the device does not allow for data to be exported, meaning individual punch data, such as the order of individual punches, could not be analyzed.

Based on the data presented, which supported the first hypothesis, participants with combat sport experience can use CPT, EPT and HPT to detect the total number of punches per session with reasonable accuracy. However, in UNTR participants, the EPT and HPT underestimated the total punch count, meaning that the CPT may be a better choice for untrained punchers in this regard. Considering that the punch trackers used in this study likely have unique algorithms for identifying different punch types [1,15] the technical implementation of each punch likely played a major role in the ability of each punch tracker to correctly register every punch. Since the EPT and HPT underestimated the total punch count in UNTR, it is possible that the thresholds needed to register a punch were not met, which could be a result of greater variability in the punch technique in UNTR compared to TR (Piorkowski et al., 2011).

Considering the punch technique, the second hypothesis was also confirmed as the CPT, EPT, and HPT were all able to better detect straight punches than hooks and uppercuts (Table 5). Specifically, the HPT had better sensitivity (recognition) than CPT for straight punches. However, the CPT was better than the HPT for correctly detecting hooks and uppercuts. Since hooks and uppercuts are delivered in a curved swinging motion with a vertical drop in the initiation of the punch, they are more technical and complex than straight punches (Piorkowski et al., 2011). Therefore, the UNTR punchers likely were unable to maintain the proper technique, resulting in worse upper cut and hook detection by the punch trackers compared to TR. Considering the strict technical requirements of hooks and uppercuts compared to straight punches, the likelihood of a "false-positive" decreases for hooks and upper cuts, which is supported by a greater specificity for hooks and uppercuts than straight punches (Table 6). In short, if a punch tracker registered a hook or uppercut, it likely actually was a hook or uppercut, since a straight punch would likely not include an arcing pattern, even for the most inexperienced punchers.

The third hypothesis was also confirmed because regardless of training experience, increasing the number of punches in a sequence negatively influenced the recognition of punch type as the order of punches progressed. Although it is possible that the participants were able to focus better on the first punch of a multipunch sequence, losing their focus as the sequence progressed, the more likely explanation is that the first punch was performed from a static position. For subsequent punches, the punch trackers may not have registered returning to the start position, which may reduce their ability to correctly detect the next punch. Furthermore, the technique of transitioning from one punch to the next simply may not have corresponded with the movements that were expected in the respective algorithms. Contrary to the negative effect of the order of punches within a sequence, as each round of shadow boxing progressed (i.e., after multiple sequences), the CPT and HPT better recognized punch types in both TR and UNTR participants. It is possible that there was a learning effect, which has previously been shown to increase punch force and velocity after only 15 min of practice (Di Bacco et al., 2020), but such rapid skill acquisition would have likely occurred only in UNTR. Nevertheless, the present data do not allow for such a conclusion, and the most logical explanation for the increased recognition over time is the pyramid nature of the protocol. Subjects performed a series of single punches, followed by two-punch combinations, three-punch combinations, two-punch combinations, and finished with single punches. As such, the latter punches of the round were in fact single punches, meaning that the number of punches per sequence likely plays a greater role in punch recognition than the overall time spent punching. Therefore, any possible learning effect may be negligible in such a short time period, and the transitions between punches (i.e., the lack of coming back to a static starting position) likely make it difficult for the punch trackers to correctly identify multiple punches in sequence.

In addition to the main findings above, there are many factors to consider when interpreting the data of the present study. First, the maximum number of punches in a sequence was three. Considering the negative effect of the number of punches in a sequence on proper recognition, the data from each punch tracker would likely differ, and possibly worsen, if the number of punches per sequence increased past three. Thus, future research should investigate the punch recognition ability of these trackers in situations where many punches are performed in sequence. Second, the EPT only provides average data from the whole session for each punch type (Table 2), meaning that punch-by-punch analyses are not possible, which is a factor to consider depending on the user's needs. Third, due to an insufficient amount of data (Table 3), the SPT data were not analyzed. Therefore, it cannot be concluded that SPT is not reliable for detecting punch types, as the SPT used in the present study may have been defective. On the other hand, it may not have been defective, and future research should aim to determine how the SPT performs under different conditions. Fourth, the CPT and HPT likely provide the most valid data for detecting and recognizing punch types. For detecting the total punch count, the CPT and HPT are both acceptable, particularly the CPT for participants without any training experience, and the HPT for more experienced participants. Although CPT, HPT, and EPT were better at detecting straight punches than hooks and uppercuts, a punch-by-punch analysis showed that the CPT and HPT not only detected but successfully recognized straight punches better than hooks and uppercuts (the EPT does not allow for such an analysis).

The CPT and HPT can both be used to evaluate shadow boxing with multiple punches, but single punches would likely be recognized more accurately. Lastly, the protocols were performed under standardized conditions, with a specific count of punches and combinations, all while boxing without an opponent. Thus, altering any combination of these conditions may affect the ability of these punch trackers to provide valid punch data, and future research should investigate these effects.

4.7 Practical application

The CPT and HPT likely provide the most valid data in terms of detecting and recognizing punch types and the total punch count during shadow boxing. Specifically, the CPT may be more suitable for participants without much experience, and the HPT may be more suitable for experienced punchers.

4.8 Conclusion

The findings can help potentional users of punch trackers choose a device based on their preferences, the possibility of exporting individual punch data, their level of experience, and the ability to detect and recognize different punch types. Nevertheless, it is important that future research investigates the punch recognition abilities of these punch trackers in other scenarios where large numbers of punches are performed in sequence, which based on the current findings, would likely reduce the accuracy of the data.

5 From punch type recognition to accurate measurement of punch velocity

The previous study showed that the StrikeTec punch tracker had far too many data sets missing, whereas the Hykso, Corner, and Everlast punch trackers detected the punch types with greater accuracy in trained punchers than untrained punchers, with better detection for straight punches then uppercuts and hooks during shadow boxing. The Everlast punch tracker did not allow for punch-by-punch analyses, which is unfortunate (from a practical perspective and from a scientific perspective, as further analyses were not possible). Nevertheless, the recognition of punch types by Corner and Hykso was affected by position of the punch in sequence, as earlier punches were recognized better than latter punches of a sequence. In the end, the Corner and Hykso seem to be most valid punch trackers for tracking the punch count, detection, and recognition during the shadow boxing.

Although shadow boxing makes up a considerable part of specific boxing training, pad punching and bag work are also important specific training condition because shadow boxing includes punching the air, without any target and impact. Needless the say, pad punching and bag work are performed with impact, which more likely mimics a real bout where punch force and velocity become increasingly important, as the goal it to knock out an opponent. Since punch trackers are meant to not only provide data regarding the punch type and number of punches, they can also be used to assess the force and velocity of punches to quantify training load and assess performance changes over time. However, the force and velocity outputs of punch trackers had not been validated, leaving a gaping hole in the body of literature, which could directly imply the real-world practical applications of these devices.

Therefore, the following study at Chapter 6 aimed to assess the validity of Corner, Hykso, and StrikeTec for tracking punch velocity and force during the rear straights, rear hooks, and rear uppercuts by trained and untrained punchers at lower (50%) and higher (100%) intensities to again determine whether the algorithms of each punch tracker function differently according to the technique of the punches thrown. Compared to the previous study, this study did not include punch tracker Everlast because it provided only an average summary of punches, not allowing for punch-by-punch comparisons. Twenty physically active participants performed six punches for each punch type (rear straights, rear hooks, and rear uppercuts) during a single testing session for each punch tracker. Each punch type was performed with an estimated 50% of maximal by three punches, followed by three punches with maximal effort. The criterion validity of the punch trackers was assessed against an optical 3-dimensional motion capture system and a wall-mounted force plate, as a replacement of boxing pads and boxing bag.

In 2023, the following text presented within Chapter 6 was published as a manuscript in the *Journal of Strength and Conditioning Research*. However, the formatting has been changed from the original submitted manuscript to allow for continuity throughout the entire dissertation.

The text, the information in the tables, graphs, and figures have not been altered in any way. Only the citation format has been modified. However, the actual references have not been altered and they are listed at the end of this dissertation.

6 Study 2: Validity of commercially available punch trackers

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Supplementary materials: Attached as Appendix 9 and Appendix 10

6.1 Abstract

This study determined how well data from commercially available punch trackers (Corner, Hykso, and StrikeTec) related to gold-standard velocity and force measures during full-contact punches. In a quasi-randomized order, 20 male subjects performed 6 individual rear straight punches, rear hooks, and rear uppercuts against a wall-mounted force plate. Punch tracker variables were compared with the peak force of the force plate and to the peak (QPV) and mean velocity (QMV) assessed through Qualisys 3-dimensional tracking. For each punch tracker variable, Pearson's correlation coefficient, mean absolute percentage error (MAPE), and mean percentage error (MPE) were calculated. There were no strong correlations between punch tracker data and gold-standard force and velocity data. However, Hykso "velocity" was moderately correlated with QMV ($r = 0.68$, MAPE 0.64, MPE 0.63) and QPV ($r = 0.61$, MAPE 0.21, MPE -0.06). Corner Power G was moderately correlated with QMV ($r = 0.59$, MAPE 0.65, MPE 0.58) and QPV ($r = 0.58$, MAPE 0.27, MPE -0.09), but Corner "velocity" was not. StrikeTec "velocity" was moderately correlated with QMV ($r = 0.56$, MAPE 1.49, MPE 1.49) and QPV ($r = 0.55$, MAPE 0.46, MPE 0.43). Therefore, none of the devices fared particularly well for all of their data output, and if not willing to accept any room for error, none of these devices should be used. Nevertheless, these devices and their proprietary algorithms may be updated in the future, which would warrant further investigation.

6.2 Introduction

As combat sports require training strategies to increase hand speed (López-Laval et al., 2020) and punch force (Dunn et al., 2022), quantifying these metrics during training is necessary to objectively determine whether the training program is effectively improving performance in these areas (French, 2016). In the laboratory, punch performance has been assessed using 3- dimensional kinematics (Bingul et al., 2017; Cheraghi et al., 2014; Lenetsky et al., 2020; Stanley et al., 2018) and force plates (Loturco et al., 2016, 2021; Menzel & Potthast, 2021b) to determine punching speed and punching impact, respectively. Indeed, those laboratory devices are commonly used in research as the gold measurement standard. However, it is impractical to use these devices to assess punch performance in real-life training such as sparring, shadow boxing, and bag work, which is where the majority of punch-specific training volume occurs. Because of the complexity, high prices, and lack of feasibility of those pieces of laboratory equipment, portable user-friendly devices can serve as an alternative and have become commercially available (Worsey et al., 2020).

In recent years, accelerometers have become increasingly popular during sports training and physical activity tracking of all types (Lake et al., 2018; Watkins et al., 2020). The majority of people who use these devices likely are not members of a scientific or academic population and would likely be attracted to the low cost and ease of use compared with devices intended for laboratory conditions (Balsalobre-Fernández et al., 2016; Camomilla et al., 2018; Shepherd et al., 2017). Furthermore, commercially available devices often analyze data within their own proprietary software, so the end user receives an understandable data output without the need for tedious analysis procedures. As a result, different devices include unique user interfaces (Espinosa et al., 2019) and a wide range of different data, despite the internal technology of those devices likely being quite similar (Peake et al., 2018; Worsey et al., 2019). However, as each device and its accompanying software is intended for specific purposes, the algorithms within likely would not be transferable between activities. For example, an accelerometer used to measure running or weightlifting performance likely could not be used in other sports modalities such as striking during combat sports (Harris et al., 2021). Therefore, specific accelerometers, known as punch trackers, have been developed to specifically assess punch performance (Shepherd et al., 2017).

Punch trackers are said to measure punch count (Omcirk et al. 2021), punch type (Omcirk et al. 2021), punch velocity (Menzel & Potthast, 2021a), and punch power (Menzel & Potthast, 2021c) in addition to other variables that companies seem to include with their own arbitrary units such intensity scores, PIQScores, and G-Force (Omcirk et al., 2021). Previous research has shown that certain punch trackers are able to accurately quantify punch count and punch type depending on training experience, with the trackers seemingly able to better detect straight punches (compared with hooks and uppercuts) and punches in trained punchers (compared with un- trained, regardless of the punch type) possibly because of better punch technique that may better fit the proprietary algorithms (Omcirk et al., 2021). Although those findings are useful, that study did not assess the effect of training experience on punch velocity and punch force, which are likely more interesting metrics for those wishing to actually monitor their training volume and intensity in practice.

Apart from that study, another one showed that a non-punch-specific accelerometer can be used to assess punch velocity (Lambert et al., 2018), but that study only included straight punches and a wired accelerometer system, both of which have obvious limitations in real-life training. In addition, previous research has shown that a different non–punch- specific accelerometer was more valid for faster movements (during a barbell back squat) compared with slower movements because the device may have had difficulty identifying the beginning of the movement during slower velocities (Banyard et al., 2017). As the technology within may be similar, it is possible that punch trackers may not correctly identify and analyze punches thrown at different intensities. Furthermore, although the amount of research on punching sensors has recently been increasing to include various punch types and custom-built wireless systems (Menzel & Potthast, 2021a, 2021c), there is still a lack of published data on the validity of commercially available punch trackers. From this point of view, research is necessary to validate the ability of commercially available trackers to accurately measure and provide end user data regarding punch force and velocity. This leads to the purpose of this study, which was to assess the validity of 3 commercially available trackers for tracking punch velocity and force during different types of punches thrown by trained and untrained punchers at higher and lower intensities.

6.3 Methods

6.3.1 Experimental approach to the problem

To investigate the validity of 3 commercial punch trackers (Hykso, StrikeTec, and Corner), subjects performed a series of punches (rear straight [RS], rear hook [RH], and rear uppercut [RUC]) during a single laboratory session. All these trackers provide some type of velocity measurement; however, it is not always known whether they assess mean velocity, peak velocity, acceleration, or another related variable. Furthermore, one of these trackers (Corner) provides a variable called Power G, which may not only relate to punching velocity but also to force. However, again, it is not known exactly where that variable comes from or how it is calculated. Therefore, the criterion validity of the punch trackers was assessed against 2 commonly used laboratory devices that directly measure velocity and force: an optical 3-dimensional motion capture system and a wall-mounted force plate.

6.3.2 Subjects

Twenty physically active men volunteered in this study (27.8 ± 5.9 years [range: 19-44], 83.2 ± 11.8 kg, 180.1 ± 8.5 cm). As mentioned in the Introduction, it is possible that punching experience may also affect the metrics provided by the trackers that were analyzed in this study. Therefore, an equal number of trained punchers (n = 10) and untrained punchers (n = 10) participated in the study. The trained punchers were experienced in combat sports involving punching for at least 1 year and had completed at least 1 competition bout in any discipline that involved punching (e.g., boxing, kickboxing, and mixed martial arts). The untrained punchers had not participated in any formal competition. Subjects had no recent injuries that would affect or be exacerbated by the study protocols. Before starting the procedures, subjects were provided with information about the risks, benefits, and procedures of the study and gave their written in- formed consent in accordance with the ethical requirements of the Ethics Committee of Charles University, Faculty of Physical Education and Sport (127/2019), and the Declaration of Helsinki.

6.3.3 Procedures

All procedures were performed during 1 session and consisted of a general warm-up; fitting with boxing gloves, wraps, and punch trackers; instructions and technique practice; a specific warm-up of shadow boxing; individualized force plate adjustments; punches performed at 50% of their perceived maximum intensity; and maximal effort punches.

General Warm-up. All subjects performed a general warm-up that included 90 seconds of rope skipping, 10 repetitions of shoulder and elbow forward and backward circles for each side, 10 front and side leg swings on each leg, 10 lunges on each leg, and 45 seconds of boxing stepping.

Fitting With Boxing Gloves, Wraps, and Punch Trackers. Immediately after the general warm-up, standard 10-ounce boxing gloves and 2.5-meter boxing wraps were used to secure the punch trackers according to the manufacturers' guidelines. The trackers were attached to the wrist on the surface of the wrist extensors. Specifically, Hykso and StrikeTec were inserted directly under the wraps, whereas Corner was first inserted into a tailor-made wristband provided by the manufacturer and then covered by the wraps and glove. Because the punch trackers have the identical recommended placement, they were not used simultaneously, resulting in 3 separate sets of punching, 1 per tracker. To avoid any potential order or learning effect (primarily for the untrained punchers), the order of punch trackers was quasi-randomized for each subject.

Instructions and Technique Practice. All subjects (trained and untrained) were provided the same verbal and physical instructions on how to perform individual punches and performed 3 minutes of guided technique practice. The subjects stood behind the researcher and performed the punches as modeled by the re- searcher. During that procedure, the subjects were supervised and potentially corrected to achieve proper technique. Considering the aims of this study, it was not imperative that every punch was performed perfectly, but it was necessary to not allow punches to be thrown in unorthodox trajectories that may not be recognized by the trackers.

Specific Warm-up. After completing the standardized technique practice, subjects performed 3 rounds of shadow boxing with 5 minutes of rest between rounds. Each round of shadow boxing included 54 punches of each punch type, serving both as a specific warm-up and additional familiarization with the punching techniques. The same verbal and visual instructions were provided for each subject regardless of experience level. The data from these shadow-boxing rounds were previously analyzed to report the ability of the trackers to correctly recognize different shadow- boxing punches in various combinations (Omcirk et al., 2021).

Individual Settings. The wall-mounted force plate was adjusted for each subject and each punch type (Figure 1), so that they would be aiming in the center of the force plate that was placed at chin-height, as is often the aim during boxing (Nakano et al., 2014). For RS, subjects stood in a normal staggered boxing stance at a self-selected distance from the force plate, and the center of the force plate was at chin-height (Loturco et al., 2016). For RH, the subjects stood to the side of the force plate to where the fist contacted the force plate with approximately a 90-degree elbow angle at the height of the subject's chin-height. For RUC, the subjects stood in a boxing stance in front of the force plate, and the angle and height of the force plate were adjusted to that there was approximately a 90-degree elbow angle when the fist was in contact with the force plate that was positioned at chin-height.

Familiarization Punching the Force Plate. Before performing the individual types of measured punches, subjects performed 5 trials of each on the force plate with progressively increasing effort. The progressively increasing punching effort provided an experience how it feels to punch the force plate with maximal effort and avoid any apprehension of subjects. In addition, the force plate was covered by padded cover to avoid potential injury because of high impacts of the fist and the force plate. As the purpose of this study was not to assess peak performance, but to assess the ability of the punch tracker data to resemble gold-standard force and velocity data, this degree of familiarization was deemed sufficient. There- fore, during the punches with maximal effort, the subjects have been instructed to subjectively punch as fast and as hard as possible.

Measured Punches. The subjects performed 6 punches for each punch type (the order of which was quasi-randomized among subjects). To determine whether various speeds and intensities of the punch would affect the resultant punch tracker data (i.e., meeting required thresholds within their algorithms), 3 punches were first performed with an estimated 50% of maximal effort, followed by 3 punches with maximal effort. A constant time of 3 seconds was provided between punches, so the subjects could fully return to a stable orthodox boxing stance.

6.4 Data acquisition and data analyses

6.4.1 Data acquisition

Three commercially available punch trackers were used in this study: Corner (Corner Boxing Trackers, Corner Wearables Ltd., Manchester, United Kingdom, v1.3.1), Hykso (Hykso Wearable Punch Trackers, Hykso Inc., CA, v1.6), and StrikeTec (StrikeTec Boxing Sensors, StrikeTec, TX, v1.4.4). Although these types of devices likely include microcontroller, accelerometers, gyroscopes, and magnetometers (Aroganam et al., 2019), the specifications of the punch trackers were not publicly available when the study was completed or when the manuscript was being prepared. The same can be said of their data filtering procedures, cutoff thresholds, and the like. Therefore, the data collected and reported in this study did not originate from raw data that we then manipulated, but were directly provided by each punch tracker's respective mobile application. The output data from Corner and Hykso were transmitted through Bluetooth to a laptop, and their respective data were exported to a .csv file and transformed to Microsoft Excel for future analysis. Data from StrikeTec were manually transcribed from its mobile application (StrikeTec Boxing) because it does not allow for direct export to a .csv file. Because of technical failures and the fact that the trackers did not always record each punch performed, data from all 20 subjects were not always included in the final analyses. Therefore, the final subject counts were as follows: Hykso (n = 20); Corner (n = 20); and StrikeTec (n = 12). Detailed information about the amount of included data set for each tracker is provided in Table 1 and is further explored in the discussion.

Punches were simultaneously assessed using the wall-mounted force plate and a video motion capture system. The adjustable wall-mounted force plate (Loadstar sensors, Fremont, CA) measured force at 1,000 Hz. Before the study, a standard incremental static calibration procedure was performed (ranging from 5 to 400 kg), and the calibration coefficients were updated within the data collection software. Subsequent spot checks with random static loads using calibrated weight plates were performed, which supported the validity of the force plate outputs against calibrated loads. All punches made contact with the center of the force plate, and the obtained data from the force plate were exported to a .csv file and transformed to Microsoft Excel (Microsoft Corporation, Redmond, WA) for future analysis where the peak punch force was recorded for each punch. Although the rate of force development and impulse could have been assessed from this force plate, we chose to only assess peak force to avoid the inherent drawbacks of impulse (e.g., less force applied over a longer period could equate to the same impulse as a large amount of force applied during a short period) and the lack of reliable RFD data during such rapid and ballistic movements. Therefore, we only analyzed the peak punch force.

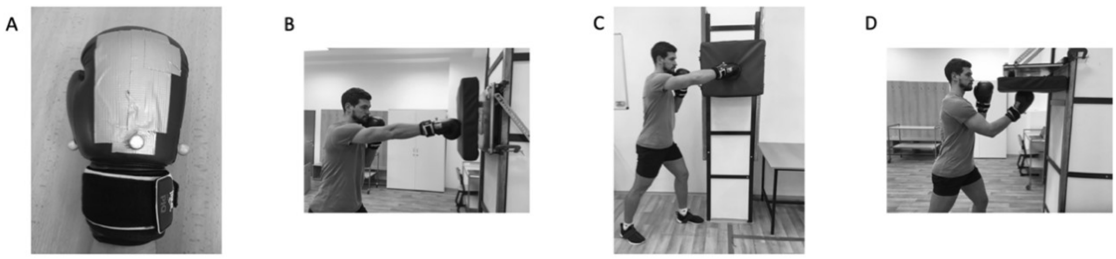
The video motion capture system (Qualisys AB, Gothenburg, Sweden) measured peak velocity (QPV) and mean velocity (QMV) of the hand using 4 cameras (Oqus) at a frequency of 500 fps. The Qualisys system was calibrated according to the manufacturer's guidelines with a standard calibration wand and foldable L-frame, which was attached on the force plate. The researcher held wand by its handle, performing twisting movements with the handle around the force plate, until the calibration process was successful. The obtained data were exported from the Qualisys Track Manager (v2019.3) to a .csv file and transformed Microsoft Excel for future analysis. The resultant QPV and QMV were assessed through 3 reflective markers that were attached on the boxing glove (Figure 3).

Table 7. Amount of included data set for each tracker

	Hykso		**StrikeTec**		**Corner**	
	TP (n = 10)	**UP (n = 10)**	**TP (n = 4)**	**UP (n = 8)**	**TP (n = 10)**	**UP (n = 10)**
RS	60 ± 0.0	60 ± 0.0	23 ± 0.4	42 ± 1.0	60 ± 0.0	59 ± 0.3
RH	57 ± 0.6	57 ± 0.5	24 ± 0.0	46 ± 0.7	60 ± 0.0	47 ± 1.8
RU	58 ± 0.6	58 ± 0.6	22 ± 0.5	42 ± 0.8	53 ± 0.3	56 ± 1.2

The actual number of punches thrown with their standard deviation for trained punchers (TP) and untrained punchers (UP) for each tracker. The standard set for each punch type consisted of 6 punches for rear straight (RS), rear hook (RH), and rear uppercut (RUC), respectively. Thus, although it appears as if ~50% of the StrikeTec punches are missing compared to Corner and Hykso, it should be noted that when the StrikeTec device was working properly, it collected approximately 96% of punches in TP and 90% of punches in UP.

Figure 3. Boxing glove with three reflective markers and force plate settings



Three reflective markers attached on the boxing glove (A) and the force plate set-up for rear straight (B), rear hook (RH), and rear uppercut (RUC)

6.4.2 Data analyses

The test-retest reliability within individual 3-punch series was calculated using intraclass correlation coefficients (A, 1) (McGraw & Wong, 1996). To evaluate the relationship between the metrics recorded by the trackers and the gold-standard criteria (either force measured from the force plate or velocity measured through motion capture system), Pearson's correlation coefficient (r) accompanied with the lower and upper bounds of the 95% confidence interval was calculated. The magnitude of correlations was described as follows: 0.00 to 0.30, negligible correlation; 0.30–0.50, low correlation; 0.50–0.70, moderate correlation; 0.70–0.90, high correlation; and 0.90–1.00, very high correlation (Hinkle et al., 2003). For metrics whose agreement was less than 0.50, no further analyses were performed. However, for the metrics whose degree of agreement was classified as at least moderate ($r > 0.50$), the percentage error for each punch was calculated as a difference between the tracker data and the criterion data divided by the criterion. The percentage errors and their absolute values were averaged to compute the mean percentage error (MPE) and the mean absolute percentage error (MAPE), respectively. The MPE value assesses the degree of overall overestimation or underestimation of the tracker against the criterion, whereas the MAPE value provides the most relevant and comparable indicator of individual error because it accounts for both overestimation and underestimation. For example, during the data acquisition of 2 punches, if the tracker showed for the first punch a mean velocity of 8 $m \cdot s^{-1}$ and the criterion mean punch velocity was 10 $m \cdot s^{-1}$ (percentage error -20%), and if the second punch was 12 $m \cdot s^{-1}$ and the criterion was 10 $m \cdot s^{-1}$ (percentage error +20%), the MPE would be 0. Thus, the MPE value would indicate that the tracker neither underestimates nor overestimate, but we cannot say anything about its performance in individual cases. In the same scenario, the MAPE would be 20%, thus showing that the tracker is not very accurate. However, the MAPE value alone would not allow us to say whether the punch tracker systematically underestimated or overestimated the criterion value.

For metrics with an MPE within 10% (Boudreaux et al., 2018), Bland-Altman plots were constructed to evaluate the mean bias, heteroscedasticity, and the limits of agreement between the tracker and the criterion for individual punch types. Heteroscedasticity was explored using Pearson's correlation coefficients between the absolute differences and the mean values (Atkinson & Nevill, 1998), and by visual inspection of a regression line fitted to the Bland-Altman plots. The limits of agreement were calculated as 2 SDs from the mean. Finally, linear mixed-effects models were used to assess the effect of training experience, punch intensity (50 and 100%), and punch type on the percentage error.

6.5 Results

The correlations between punch tracker data and the gold- standard velocity and force data are shown in Table 8. None of the data from Hykso, Corner, or StrikeTec were highly correlated with the gold-standard velocity or force data.

Table 8. The correlations between punch tracker data and the gold-standard velocity and force data

	Hykso	StrikeTec	Corner	
	Peak Velocity	**Speed**	**Power G**	**Speed**
QPV	r = 0.61 (0.54 to 0.68)*	r = 0.55 (0.44 to 0.64)*	r = 0.58 (0.51 to 0.65)	r = 0.03 (-0.08 to 0.13)
QMV	r = 0.68 (0.62 to 0.74)*	r = 0.56 0.45 to 0.65)*	r = 0.59 (0.51 to 0.65)	r = -0.05 (-0.16 to 0.05)
FP	r = 0.23 0.13 to 0.33)*	r = 0.36 (0.23 to 0.48)*	r = 0.28 0.17 to 0.37)	r = 0.43 (0.34 to 0.52)

The Pearson's correlation and confidence intervals (95%) for the Hykso, StrikeTec, and Corner, and their non-defined velocity/speed or power values compared against gold-standard peak velocity (QPV), mean velocity (QMV), and peak punch force (FP) values for all 3 punch types combined. (*$p<0.001$)

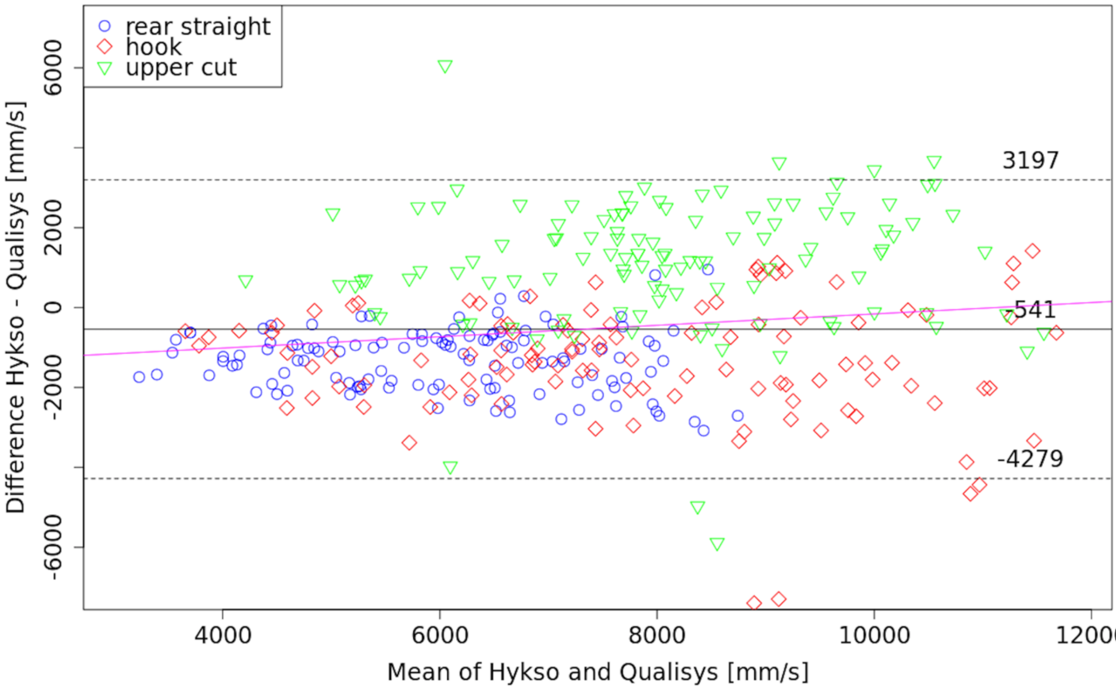
For the metrics whose degree of agreement was at least moderate ($r > 0.50$: Hykso peak velocity, Corner Power G, and StrikeTec velocity), the MPE and MAPE were calculated (Table 9). Then, based on the MPE values (<10%), Bland- Altman plots, with the mean difference and their limits of agreement, were constructed only for QPV and each punch type for both Hykso peak velocity (Figures 4, 5, 6, and 7) and Corner Power G (Figures 8, 9, 10, and 11). Heteroscedasticity was small but significant for both Hykso peak velocity ($r = 0.21$, 95% CI 0.10 to 0.31, $p < 0.001$) and Corner Power G ($r = -0.14$, 95% CI -0.24 to -0.03, $p = 0.012$). Therefore, the percentage error was log-transformed before entering the regression models as the outcome variable.

Table 9. Mean percentage error (MPE) and mean absolute percentage error (MAPE) for Hykso, StrikeTec, and Corner and their variables

	Hykso Peak Velocity		StrikeTec Speed		Corner Power G	
	MPE	**MAPE**	**MPE**	**MAPE**	**MPE**	**MAPE**
QPV	-6%	21%	43%	46%	-9%	27%
QMV	63%	64%	149%	149%	58%	65%

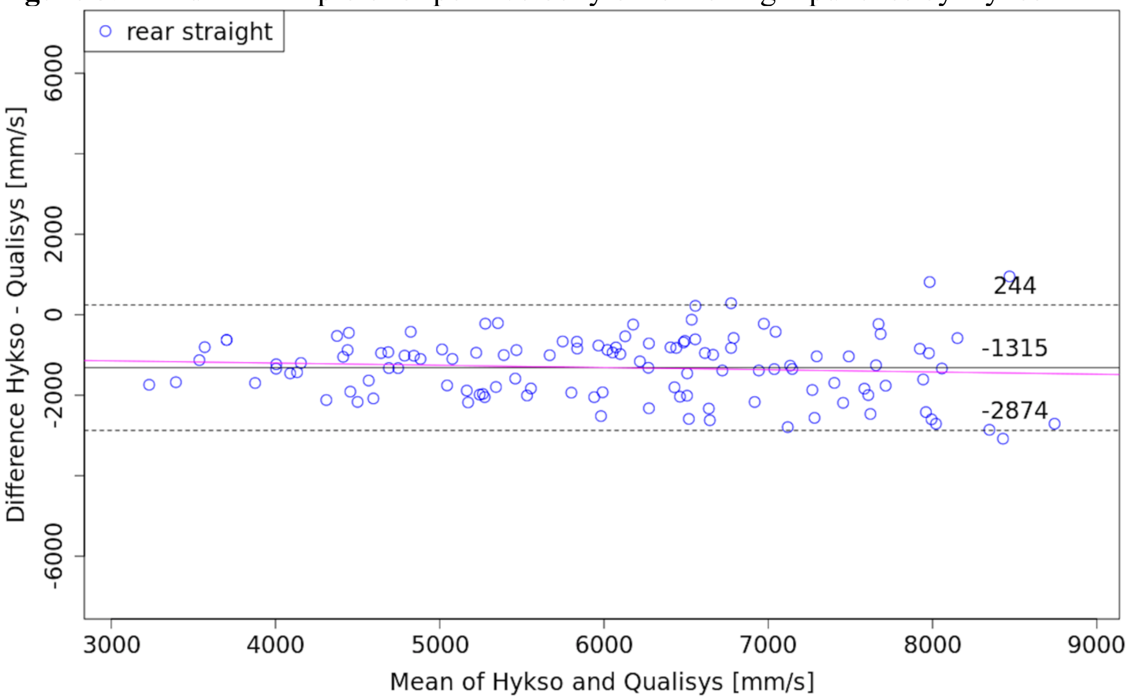
For reference, MPE and MAPE values closer to zero are the most desirable.

Figure 4. Bland-Altman plots for peak velocity of all punches by Hykso



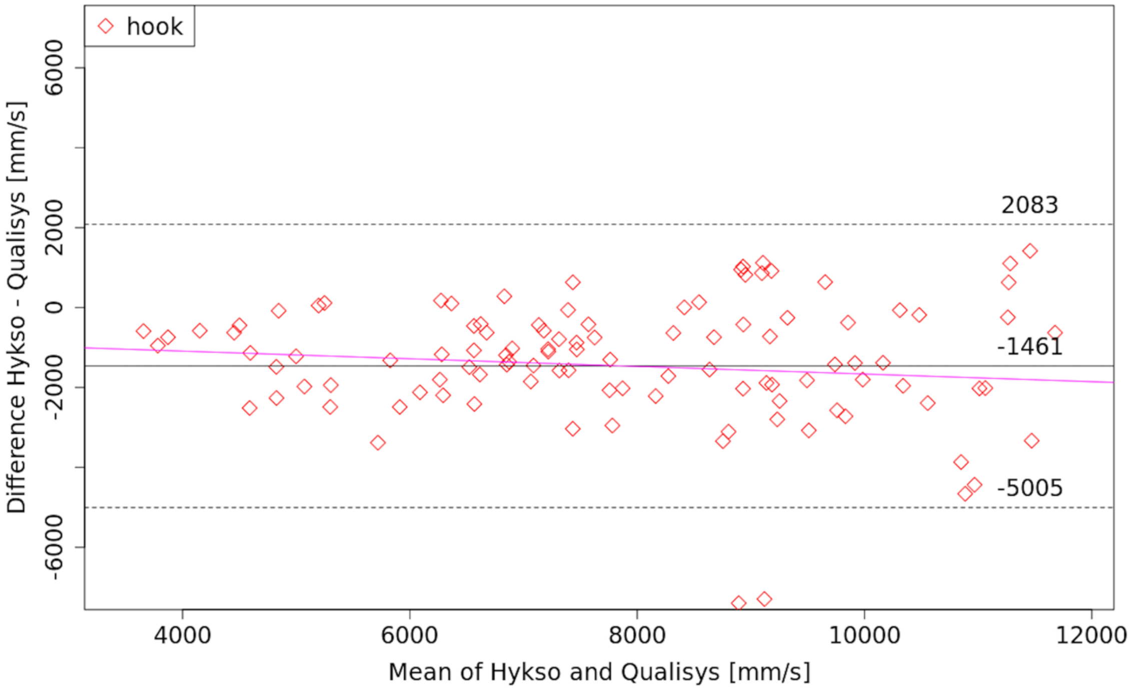
"Velocity" determined by Hykso. The solid line indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manage and the outcomes of the trackers. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 5. Bland-Altman plots for peak velocity of rear straight punches by Hykso



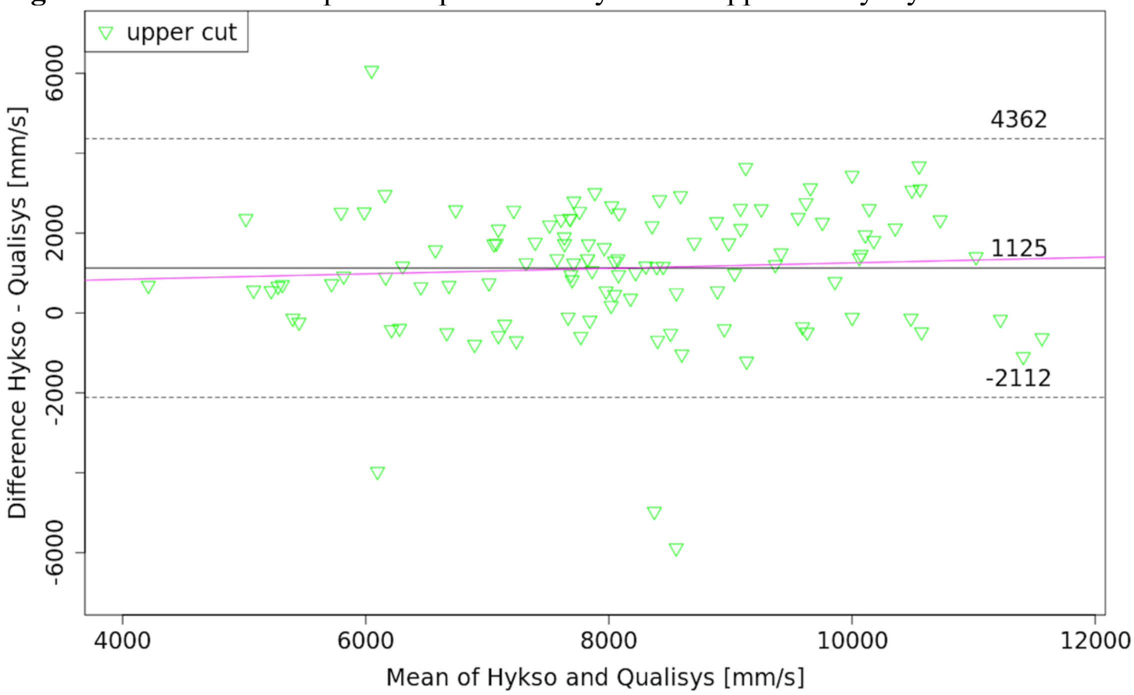
"Velocity" determined by Hykso. The solid line indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manage and the outcomes of the trackers. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 6. Bland-Altman plots for peak velocity of rear hooks by Hykso



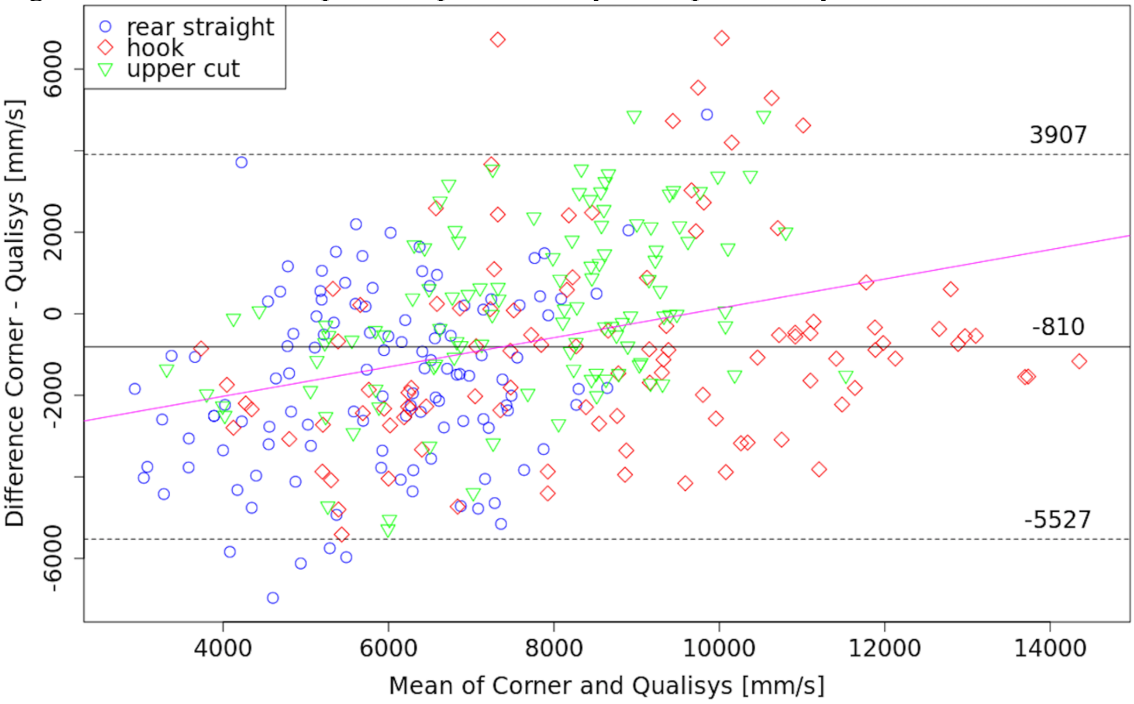
"Velocity" determined by Hykso. The solid line indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manage and the outcomes of the trackers. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 7. Bland-Altman plots for peak velocity of rear uppercuts by Hykso



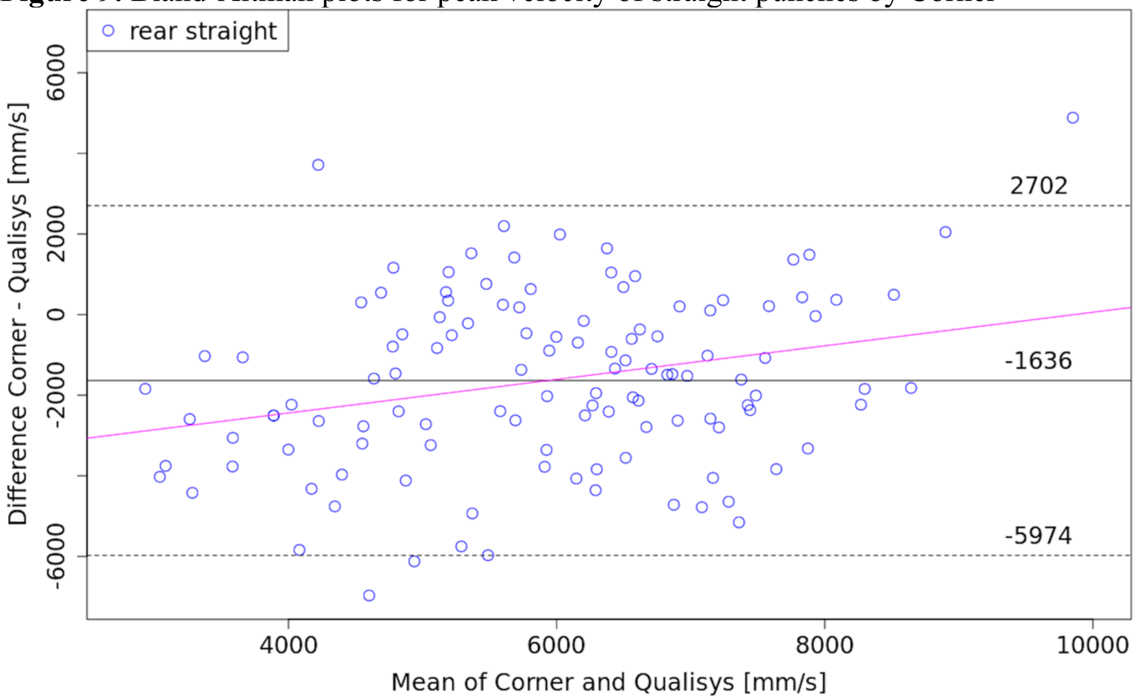
"Velocity" determined by Hykso. The solid line indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manage and the outcomes of the trackers. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 8. Bland-Altman plots for peak velocity of all punches by Corner



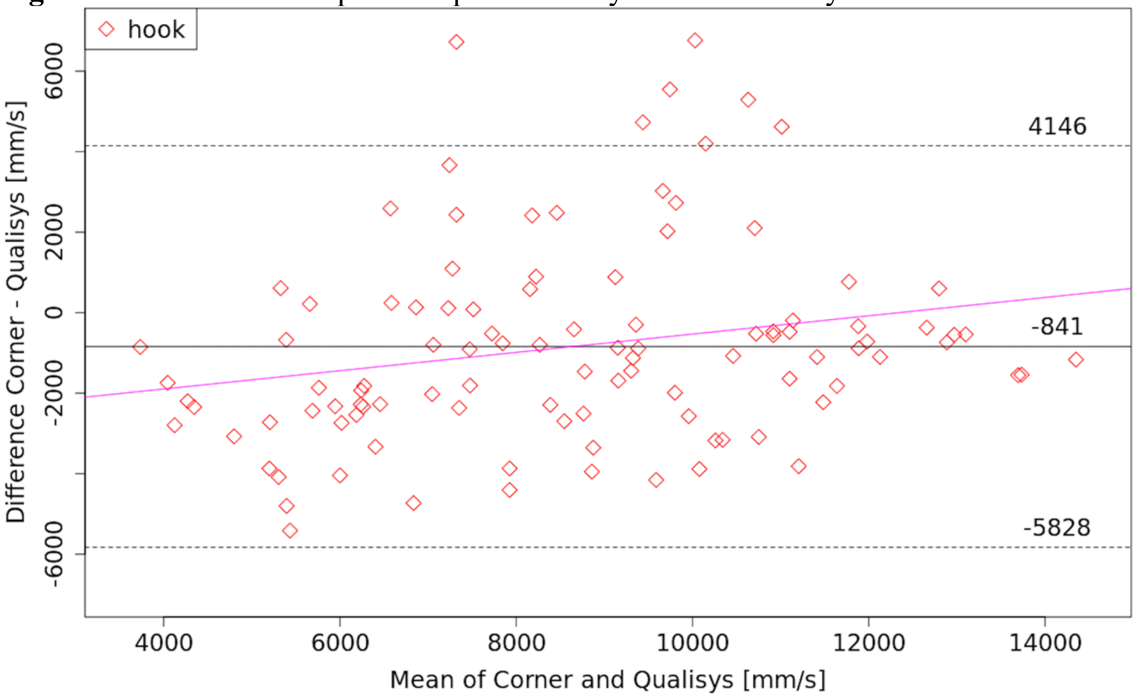
"Power G" determined by Corner. The solid lines indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manager and the outcomes of the tracker. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 9. Bland-Altman plots for peak velocity of straight punches by Corner



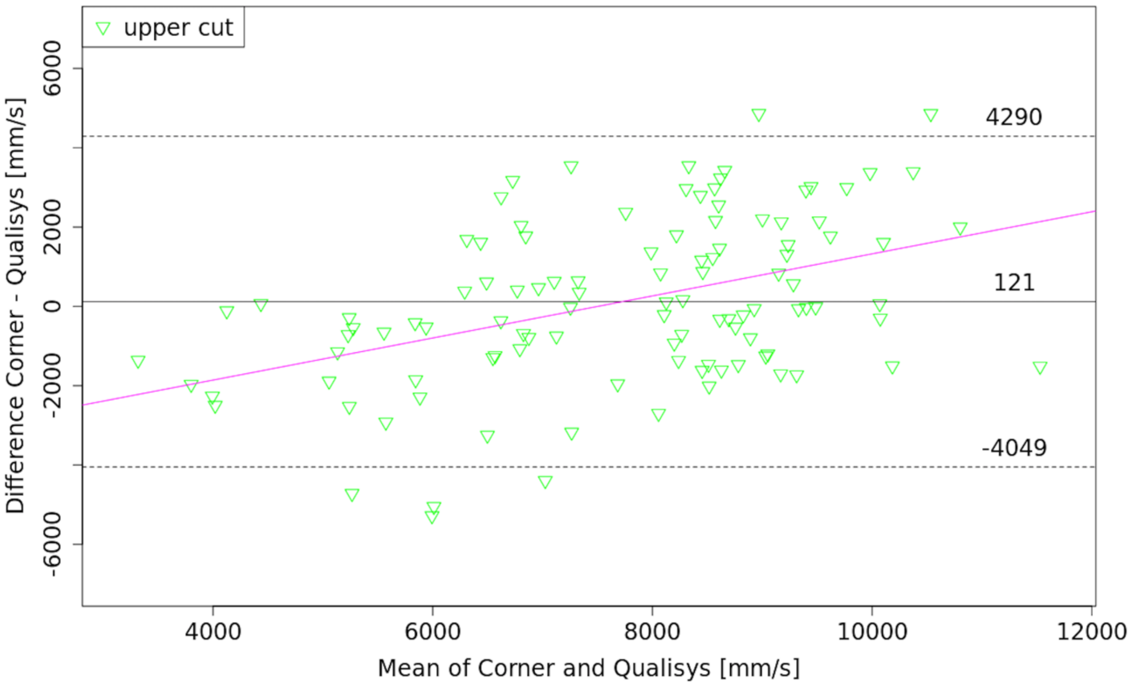
"Power G" determined by Corner. The solid lines indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manager and the outcomes of the tracker. The dashed lines represent limits of agreement (± 1.96*SD).

Figure 10. Bland-Altman plots for peak velocity of rear hooks by Corner



"Power G" determined by Corner. The solid lines indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manager and the outcomes of the tracker. The dashed lines represent limits of agreement (± 1.96*SD).

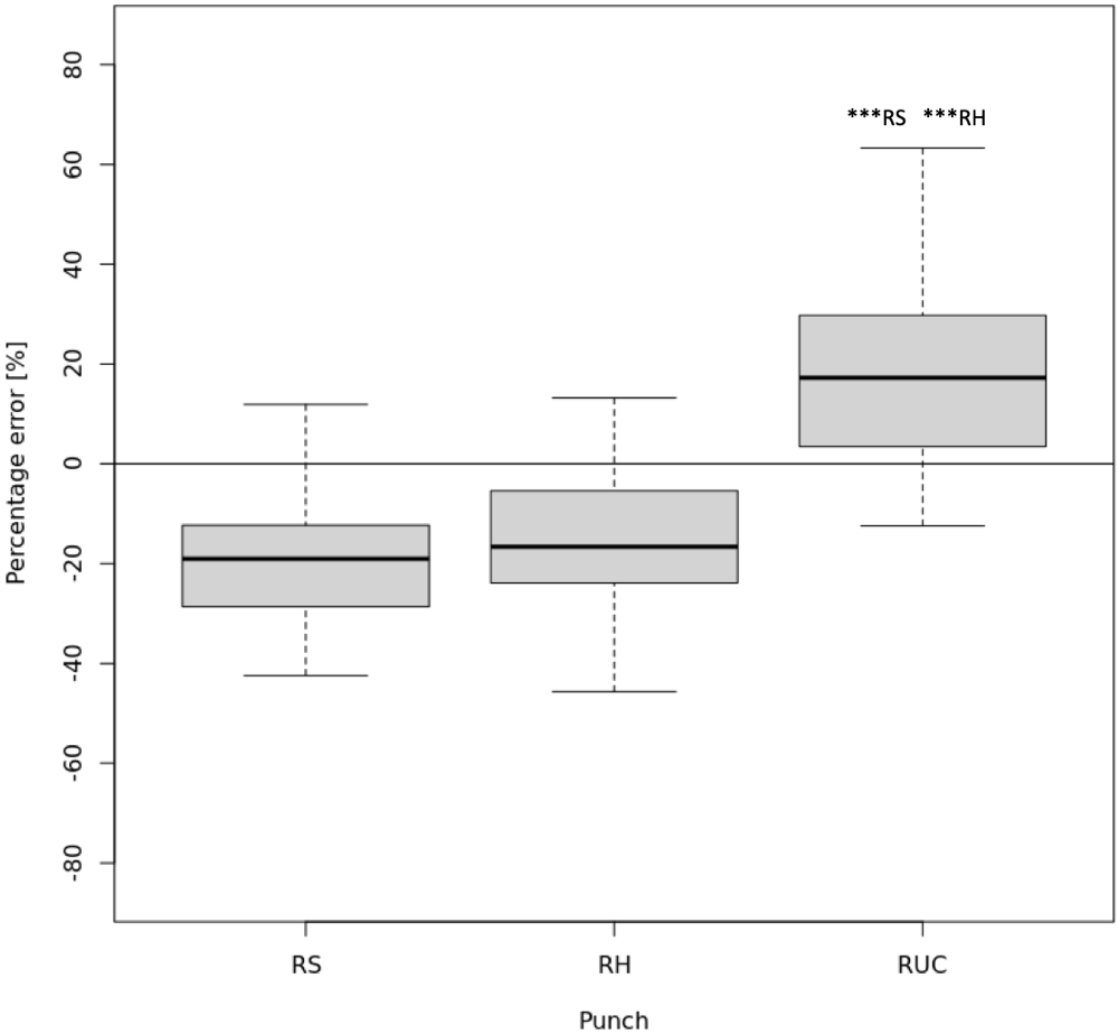
Figure 11. Bland-Altman plots for peak velocity of rear uppercuts by Corner



"Power G" determined by Corner. The solid lines indicated the mean difference between the peak velocity (mm/s) as assessed by Qualisys tracking manager and the outcomes of the tracker. The dashed lines represent limits of agreement (± 1.96*SD).

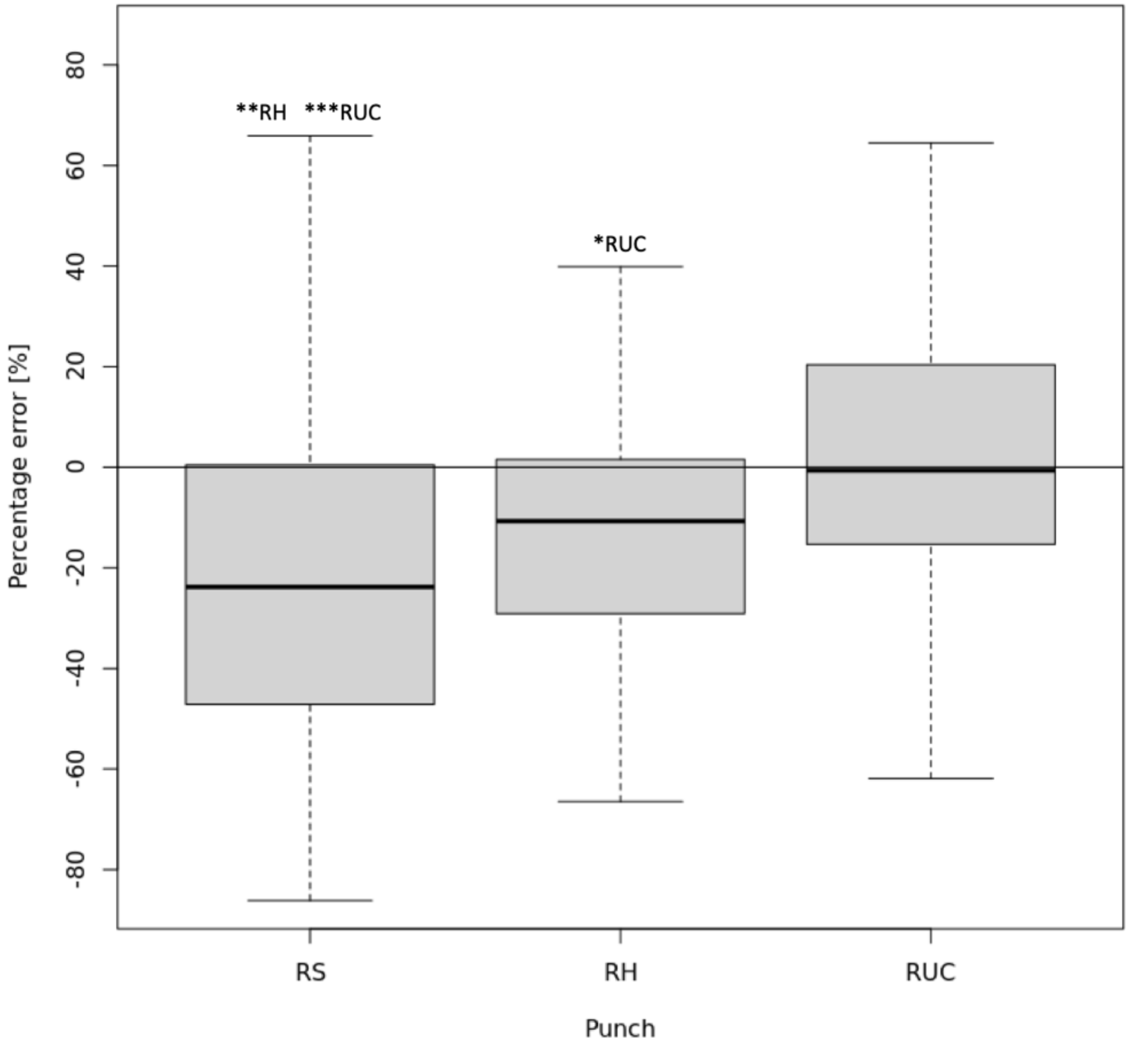
The linear mixed-effects model indicated that for QPV, the percentage error for Hykso peak velocity (Figure 4) and Corner Power G (Figure 5) was significantly affected by punch type ($p < 0.001$). Specifically, for Hykso peak velocity, there was a significant difference between RUC and RS ($p < 0.001$) and between RUC and RH ($p < 0.001$). For Corner Power G, there was a significant difference between RUC and RS ($p < 0.001$), RUC and RH ($p = 0.028$), and RH and RS ($p = 0.003$).

Figure 12. Percentage error for Hykso and the gold-standard



The percentage error for "Velocity" determined by Hykso with peak velocity assessed by Qualisys tracking manager as the gold-standard. RS (rear straight), RH (rear hook), and RUC (rear uppercut). Significantly greater (*** $p \leq 0.001$) than RS and RH.

Figure 13. Percentage error for Corner and the gold-standard



The percentage error for "Power G" determined by Corner with peak velocity assessed by Qualisys tracking manager as the gold-standard. RS (rear straight), RH (rear hook), and RUC (rear uppercut). Significantly greater (* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$) than RH and RUC.

Furthermore, the linear mixed-effects model indicated that for QPV, the percentage error was not significantly affected by training experience for Hykso, ($p = 0.162$) or Corner ($p = 0.202$). In addition, for QPV, the percentage error was not significantly affected by punch intensity (50 vs 100%) for Hykso ($p = 0.405$), but it was for Corner Power G ($p = 0.042$) (results of separate analyses for 50 and 100% intensities are reported in Supplemental Digital Content 1, http://links.lww.com/JSCR/A400). The test- retest reliability within the 3-punch series for individual trackers, punch types, and intensities varied widely from none to excellent, which is later explained in the discussion. (see Supplementary Digital Content 2, http://links.lww.com/JSCR/A401).

6.6 Discussion

This study was conducted to elucidate whether commercially available punch trackers could provide data that would relate to gold-standard punch velocity and punch force. In most settings, for data to be valid, the data collection procedures must be reliable. In this study, we purposefully asked subjects of different training levels to perform various punches at different intensities, and we did not focus on whether peak performance was attained. For example, if a subject was instructed to punch at 50% of their maximum perceived effort but they in fact punched at 70%, the trial was still included in the analyses because the main purpose was to compare punch tracker data with gold-standard force and velocity data, not to compare the ability of a subject to perform a movement perfectly for multiple trials. As a result, the reliability of subjects to execute punches with the same force or velocity ranged from poor to excellent (see Supplemental Digital Content 2, http://links.lww.com/JSCR/A401). However, it is important to consider that the reliability of subjects to punch reliably does not play a role in the ability of each punch tracker to reliably provide valid data compared with gold-standard measurements. There- fore, the results of this article must be viewed from a "device reliability" perspective rather than a "subject's ability to reliably perform a movement" perspective.

Among the many results presented in this article, the main findings include the following: (a) Although none of the punch tracker data were highly correlated with any of the criterion metrics, (b) Hykso peak velocity, StrikeTec speed, and Corner Power G were moderately correlated with QMV and QPV. Furthermore, although Hykso (peak velocity) and Corner (Power G) seemed to provide data that were moderately correlated with both QMV and QPV, (c) the percentage errors for both were smaller for QPV, indicating that data from both may best represent QPV. However, (d) the punch type seemed to influence the accuracy of Corner Power G and peak velocity of Hykso. Of note, the percentage error was greater for RUC than for RS and RH. Finally, (e) the QPV percentage error was not affected by training experience or punch intensity when using Hykso. However, for Corner, the QPV percentage error was affected by punch intensity, but not training experience. Therefore, although none of the punch tracker data were highly representative of QMV or QPV, the percentage error of QPV was not largely affected by different punch types, training status, or punch intensity when using the Hykso punch tracker.

The first point to consider, which is essential to clarify before progressing in the discussion, is that the Corner and StrikeTec punch trackers did not always provide specific units of measurement for their variables, nor did they always specify whether the variables were derived from the mean or peak. As with most sport-related movements, there are by Corner and StrikeTec will be kept constant throughout the discussion. Although we chose to stick with the "speed" variable name provided by the manufacturers, and although neither device specifies that it measures peak velocity, the percentage error (Table 3) indicates that they likely represent QPV more so than QMV. Nevertheless, it is worth noting that in addition to Hykso's specification of peak velocity, Everlast PIQ punch trackers specify that they assess average velocity, but at the time of this study, there was not an option to assess the data of individual punches or to export the data of individual punches (Omcirk et al., 2021), meaning they were not included in the analyses for this study. Therefore, the remaining discussion points should be considered with caution because future updates to the software, algorithms, or variable names of these punch trackers may result in different data and conclusions than those that are presented at the time that this article was being prepared.

Regarding the peak impact force, none of the punch tracker data in this study were highly correlated with peak force data from the wall-mounted force plate (r = 0.23 to 0.43; Table 2). In terms of monitoring performance and quantifying training loads, this is far from ideal because the punch trackers used in the cur- rent study do not seem to be able to accurately quantify the impacts that could occur during boxing training. Although force plates are valid devices for assessing punch impact force (Loturco et al., 2016, 2021), it is impractical to rely on them to quantify the impact forces accrued during training. Thus, of the punch trackers tested in this study, the "speed" data from the Corner punch tracker included the highest correlation (r = 0.43) with impact force, whereas the Power G variable had the weakest (r = 0.28). This is interesting because the Power G variable would intuitively be more closely related to force, whereas Corner "speed" data should be more indicative of punch velocity. However, based on our data, it seems as if their variable names are somewhat misleading for the user because the Power G variable was better correlated with QPV (r = 0.58) and QMV (r = 0.59) than it was with impact force. Therefore, although Corner "speed" had the highest correlation to peak impact force out of all the punch tracker variables assessed, the data indicate that none of those variables seem to be representative of peak impact force.

Regarding punch velocity, our data indicate that punch trackers (i.e., indirect measures of velocity) do not fully align with direct criterion measures of velocity (i.e., 3-dimensional kinematics), which agrees with previous research (Harris et al., 2021). Specifically, Corner speed did not correlate well with QMV or QPV. On the other hand, although Hykso is likely acceptable for monitoring both peak and mean velocity (i.e., similar moderate correlations), Hykso specifies that it measures peak velocity, which agrees with the smaller percentage errors with QPV of Table 3. Considering the percentage errors (Table 3), it also seems as if Corner Power G (MPE = -9%) and StrikeTec speed (MPE = 43%) may also better represent QPV, despite having similar moderate correlations (Table 2) with both QPV and QMV (Corner Power G—QPV r = 0.58; Corner Power G—QMV r = 0.59 and StrikeTec speed—QPV r = 0.55; StrikeTec speed—QMV r = 0.56). Nevertheless, some degree of error still exists, even for Hykso, which demonstrated the smallest percentage errors of the punch trackers assessed in this study. From a practical perspective, although multiple punch trackers can provide instantaneous feedback and increase the motivation of athletes (Weakley et al., 2019a; J. Weakley et al., 2019b), it seems as if Hykso could be used to provide feedback for peak punch velocity, but the error would still need to be considered.

As our analyses also showed that the MPE for QPV was greater than 10% for StrikeTec speed, we only further analyzed the effect of punch type, training experience, and punch intensity on Hykso velocity and Corner Power G. Hykso seemed to have less error when detecting velocity during RS and RH punches than RUC, but Corner had variable degrees of error depending on the punch type and punch effort. To elaborate on this, Figure 2 shows that the rate of measurement error is greater when punches are thrown with faster velocities. From a practical sense, this should be considered, especially for well-trained punchers. In addition, Hykso tends to overestimate RUC against the RS and RH. The boxing punch involves the full-body kinetic chain (Filimonov et al., 1983) where the ankle, thigh, trunk, forearm, and hand must move in a coordinated fashion (Gu et al., 2018). Therefore, each punch type requires a unique co- ordination pattern and punch trajectory (Dinu & Louis, 2020a; Lenetsky et al., 2020). Based on previous research, the training experience and punch type can affect the abilities for punch trackers to correctly recognize and assess punches (Omcirk et al., 2021). However, although this study shows that error was still present when assessing QPV, the percentage error was not significantly affected by training experience. Therefore, although each punch tracker likely has different algorithms to detect and assess different punch types, they are not publicly available, which means that any further discussion on the topic cannot be justified at this moment.

Among the few remaining points to be considered, the total number of punches detected by the StrikeTec punch tracker was far fewer than the Hykso and Corner devices. Table 1 shows that StrikeTec essentially did not register 50% of the punches thrown within this study, most of which were likely due to technical difficulties. This is similar to a previous study where StrikeTec punch trackers were able to detect only about 50% of straight punches and about 3% of hooks and uppercuts during shadow boxing (i.e., punching without any contact or impact forces) (Omcirk et al., 2021). Therefore, the ability of the StrikeTec punch trackers to provide relevant data seemed to improve in this study when punch impact occurred, which indicates that perhaps, the algorithms within the StrikeTec software may require some degree of impact to register a punch (i.e., it collected data on ~96% of punches in TP and 90% in UP, compared with Corner [96% for TP, 90% for UP] and Hykso [97% for TP, and 97% for UP]). Nevertheless, the velocity data provided by StrikeTec were moderately correlated with QMV and QPV, but with greater percentage errors than Hykso and Corner. Furthermore, the StrikeTec analyses only included values that were present. Thus, if "null" data were included for punches that were not registered (approximately 50% of the punches thrown), the correlations would have been far weaker, which is worth considering.

Although the purpose of this study was not to recommend purchasing any of the tested trackers, it is important to consider that the presented data were obtained in the laboratory conditions with standardized procedures. The subjects performed 3 punches with approximately 50% of maximal effort and 3 punches with maximal effort for each punch type, which is in line with similar research investigating other devices during straight punches (Lambert et al., 2018). The trackers do not allow the users to input any other data of the subjects, such as fist size and arm length, suggesting that the softwares use some predefined values, which could have affected the results because punch tracker velocity is likely measured as angular velocity, but reported as linear velocity that would be affected by the radius length (McGinnis, 2005). Furthermore, any attempt to alter the position of the punch trackers would have decreased the ecological validity of the study because real-world users would also likely follow the placement guidelines provided by the manufacturers. Normally, this type of laboratory-based study is the first step in validating such devices, and future re- search would normally take the next step to investigate the validity of a more realistic and dynamic environment. However, we cannot currently recommend that next step because these devices may perform even worse in a more dynamic real-life situation (e.g., not performing single punches at a stationary target, but striking different areas of a moving opponent).

None of the punch tracker data in this study were highly correlated with gold-standard velocity or force measures. However, although all punch trackers provided data that were moderately correlated to peak and mean velocity, Hykso seemed to have the least amount of error, which was least affected by punch type, training experience, and punch intensity. Furthermore, Corner users should know that their Power G variable likely refers to punch velocity, whereas their velocity variable may refer to something else that may be more representative of punch force. Considering our results, future developments (i.e., software and hardware updates, specifically from these manufacturers) are needed to provide valid commercially available trackers for monitoring punch force and velocity.

6.7 Practical application

Coaches and athletes can likely use the Hykso and Corner punch trackers to monitor peak velocity, assuming that they are willing to accept the errors that occur within (specifically Hykso's overestimation of RUC velocity). However, if not willing to accept any room for error, none of these devices should be used. Furthermore, caution should be used when working with elite punchers because the measurement of error increases when punches are thrown at faster velocities. Thus, the faster the punch, the greater the risk of a larger measurement error. When StrikeTec is able to successfully collect data were missing in our study (possibly because of a faulty device, connection problems, or other unknown factors), so caution should be used. Regarding punch force, none of the variables from this study should be used to asses punch force.

7 From punching-specific to movement-specific strength and power testing

As stated in the previous chapter, none of the punch trackers performed particularly well in terms of assessing punch force or velocity. Although, the results indicated that the Hykso and Corner could be used to monitor peak velocity if the errors of accuracy would be accepted.

Moving from punching-specific testing, to movement-specific strength and power testing, monitoring, and testing of strength and conditioning exercises is also useful, because boxers spend the time at the gym with lifting weights to ultimately improve their punching ability. Because boxing punch is a whole body movement, the landmine punch throw would seem to be a suitable exercise to use for upper body ballistic testing, which closely mimics the movement patterns of punching. As such, the landmine punch throw can be used for monitoring and testing the performance over time and establishing of load-velocity profile, which can help explore the explosive strength of a boxer for using exercise which is similar as boxing punch.

As punch trackers were innovated for the specific purpose of monitoring *punch* velocity and *punch* force, using those punch trackers to assess the landmine punch throw would not be correct. Furthermore, previous studies have compared the validity of accelerometers and linear position transducers for monitoring lifting velocity, and linear position transducers presented more reliable and valid peak velocity data compared to accelerometers (Banyard et al., 2017; Weakly et al., 2021).

As no studies had investigated the reliability of the landmine punch throw (as a test should be valid if it were to be used to monitor performance over time), the main purpose of the following study was to verify the reliability of different commonly used landmine punch throw variations. Furthermore, in doing so, the study also was able to evaluate the load velocity profile performed with dominant and non-dominant hand, which would add a much-needed ballistic unilateral exercise to the body of load-velocity profiling literature.

Fourteen healthy boxers performed a single testing visit. Following a standardized warm-up, each boxer performed three different landmine punch throw variations and three different loads. Each variation was performed with the dominant and non-dominant hand. The peak velocity of each variation was assessed by the linear position transducer.

In June 2023, the following text presented within Chapter 8 was submitted as a manuscript in the *Journal of Strength and Conditioning Research*. However, the formatting has been changed from the original submitted manuscript to allow for continuity throughout the entire dissertation.

The text, the information in the tables, graphs, and figures have not been altered in any way. Only the citation format has been modified. However, the actual references have not be altered.

8 Study 3: Reliability of three landmine punch throw variations and their load-velocity relationship performed with the dominant and non-dominant hands

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8.1 Abstract

This study assessed the reliability and load-velocity profiles of three different landmine punch throw variations (seated without trunk rotation [LPwo], seated with trunk rotation [LPw], and standing whole body [LP]) with different loads (20 kg, 22.5 kg, and 25.0 kg), all with the dominant (DH) and non-dominant hand (NH). In a quasi-randomized order, fourteen boxers (24.1 ± 4.3 y, 72.6 ± 10.1 kg) performed three repetitions of each variation with DH and NH, with maximal effort and 3 minutes inter-set rest. Peak velocity (PV) was measured via GymAware power tool. The intra-session reliability of each variation-load-hand combination was determined along with the intraclass correlation coefficients and their 95% confidence intervals. Additionally, a 2(hand)*3(variation) repeated measures ANOVA assessed the load-velocity profile slope, and a 3(variation)*2(hand)*3(load) repeated measures ANOVA assessed the PV of each variation. Most variations were highly reliable (ICC > 0.91), with the NH being as reliable or more reliable than the DH. Very strong linear relationships were observed for the group average for each variation ($R^2 \geq 0.96$). However, there was no variation*hand interaction for the slope, and there was no main effect for variations or hands. Additionally, there was no interaction for the PV, but there were main effects for variation, hand, and load ($p < 0.01$). Each variation was reliable and can be used to create upper body ballistic unilateral load-velocity profiles. However, as with other load-

velocity profile research, individual data allowed for more accurate profiling than group average data.

8.2 Introduction

There are numerous methods of assessing muscular strength such as repetition maximum tests (Jukic et al., 2020c), isokinetic strength (Merrigan et al., 2020, 2022; Tufano et al., 2020a), and others (Bartolomei et al., 2022). Although a large selection of strength tests exists, testing ballistic power output is largely limited to movements that encompass jumps (Cormie et al., 2009; Janikov et al., 2023) and throws (García-Ramos, Pestaña-Melero, et al., 2018; Ikeda et al., 2006; West et al., 2013). Indeed, jump testing is widely used, especially for most athletes who perform jumps during training, which likely reduces the variability and need for further familiarization prior to testing. However, jumps are essentially limited to the lower body, necessitating similar solutions for upper body power assessments. To test upper body power output, one common choice includes throwing a medicine ball for distance (Harris et al., 2011), but the resultant data can largely depend on the throwing technique and size of the implement, variations of which may result in large variability and unreliable test results. It is true that bench press throws include fewer degrees of freedom especially if performed on a Smith machine, for example, which should result in more reliable data. However, bilateral exercises cannot always be used for testing unilateral movements (Sugiyama et al., 2014) which might be desired for specific purposes such as quantifying asymmetries (Guan et al., 2022; Lockie et al., 2014; Stephens et al., 2005), assessing training adaptations between limbs (Moreno-Azze et al., 2021), or performing exercises where each limb may necessitate a different loading pattern.

The landmine punch throw is a fairly novel unilateral ballistic upper body exercise that is commonly used not only in training, but also for testing. During the landmine punch throw, an athlete grabs the end of one barbell sleeve and throws it with a linear upward push (approximately 40-60° from parallel) while the other sleeve (i.e., the opposite end of the barbell) is fixed to a 3-dimensional moveable attachment on the floor (Ruddock et al., 2018). As such, this exercise allows for upper body unilateral ballistic testing, requires minimal equipment, and is extremely portable. The movement is often performed in a standing position using the whole body, but different variations of the landmine punch throw can allow for isolated testing of the upper body, upper body and trunk, and the whole body including the lower limbs. In terms of testing, a linear position transducer can be attached to the thrown end of the barbell to assess peak velocity, and the sleeve can be loaded to assess a wider range of external forces which could ultimately lead to the creation of individualized upper body ballistic force-velocity profiling. In fact, using a unilateral load-velocity profile could be very useful for exploring asymmetry between limbs. Additionally, this load-velocity profile could also be useful to track adaptations over time, specifically when using different body segments.

In practice, the landmine punch throw is already used in training and testing for sports that share similar movement patterns such as combat sports, rugby, American football, and other sports where the arm and hand require rapid extension in front of the body. However, to the best of our knowledge, the reliability of the landmine punch throw test in addition to the load-velocity profile derived from the landmine punch throw have not been scientifically addressed in the literature. Specifically, the reliability of different variations of the exercise performed with different loads with the dominant and non-dominant hand, and their load-velocity relationships, are all some of the foundational points that should be addressed before promoting the widespread use of testing procedures that may be unreliable.

Therefore, one aim of the present study was to determine the peak velocity reliability of the three independent variations of the landmine punch throw (arm, arm with trunk rotation, and whole body) each with three different loads (only barbell [20 kg], 22.5 kg, and 25 kg) with the dominant and non-dominant hand. Additionally, the more practical aim of the study was to evaluate the load-velocity profile of three landmine punch throw variations with three different loads with the dominant and non-dominant hand to determine whether they could be used to monitor training adaptations.

8.3 Methods

8.3.1 Experimental approach to the problem

During a single laboratory visit, fourteen trained boxers performed, in a quasi-randomized order, the three different landmine punch throw variations with three different loads, all with the dominant and the non-dominant hand. The peak velocity of the landmine punch throws was assessed using a linear position transducer.

8.3.2 Subjects

All 14 healthy boxers (24.1 ± 4.3 y, 72.5 ± 10.1 kg, 176.9 ± 8.3 cm, 12 orthodox and 2 southpaw boxers) had at least one competitive boxing bout and at least one year of structured strength and conditioning training during which they regularly performed the landmine punch throw exercise. Each subject was informed of the potential risks and possible benefits of this project, and then read and signed a written informed consent approved by the local university ethics committee (ER19357858).

8.3.3 Procedures

All procedures were performed during one testing visit and consisted of 3 phases: (1) warm-up, (2) individual set-up and familiarization, and (3) landmine punch throw assessment.

Warm-up. The standardized warm-up included 120 seconds of rope skipping, mobilization exercises for the upper-limbs, lower-limbs, hips, and dynamic stretching for the upper- and lower-body for 10 minutes, which was followed by 6 squat jumps and 6 countermovement jumps.

Individual set-up and familiarization. The landmine punch throw was performed in three different conditions: whole body landmine punch throw (LP), landmine punch throw in a seated position with trunk rotation (LPw), and landmine punch throw in seated position without trunk rotation (LPwo), all of which were performed with both the dominant and non-dominant hands independently. In the standing position, each subject stood in their preferred boxing stance (orthodox or southpaw). In the seated position, the seated height of the subject was adjusted with jerk blocks to ensure a 90° knee joint angle. A hand-operated Goniometer was used to determine knee joint angle for each subject. Then, subjects fully extended their legs and rested their heels on a slightly elevated surface to minimize the use of the lower limbs during the movement. The proper technique was demonstrated for each variation. Before each testing set, subjects performed 3 trials of landmine punch throw for each variation and load, with an estimated 50% maximal effort.

Landmine punch throw assessment. Each subject performed 3 repetitions of the landmine punch throw for each hand with 3 loads (20, 22.5, 25 kg) with 3 minutes of inter-set rest. The testing loads were set up based on pilot testing that showed that greater differences between each load did not allow participants to perform the seated variations correctly. A constant time of 3 seconds was provided between each repetition. The initial position for the LP was similar to a true boxing stance. The barbell was held in the rear hand as close as possible to shoulder height, with the elbow fully flexed and knees slightly flexed. The lead hand was positioned at chin with elbow flexed. Upon instruction, subjects proceeded to rotate their trunk on the rear side from a stationary position into a squat before forcefully extending the ankle, knee, hip, and elbow, whilst simultaneously throwing the barbell in a forward direction (Ruddock et al., 2018). The LPw was performed with the same initial position of the lead and the rear hand and the same technique (i.e., with rotation of the upper body, but now without lower body involvement). The LPwo was the same as for the LPw, but a broomstick was positioned behind the back of each participant to avoid the rotation of the trunk (Figure 14). The subjects were required to maintain the same level of contact with the broomstick throughout the movement in order to minimize occurrence of trunk rotation. Each variation was performed with the dominant (DH) and non-dominant hand (NH).

Figure 14. The landmine punch throw variations

A = landmine punch throw; B = landmine punch throw with the rotation of trunk; C = landmine punch throw without rotation

8.4 Data acquisition and data analyses

8.4.1 Data acquisition

The peak velocity (PV) of all variations of landmine punch throw and different loads was collected with a validated linear position transducer (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia) (Orange et al., 2020). The cable of the GymAware was attached to the barbell, where the body of the barbell meets the end of the barbell. The obtained data from the GymAware were transmitted via Bluetooth to a tablet (iPad, Apple, Inc., Cupertino, California) using the GymAware v2.4.1 app, and to the online cloud before being exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) for future analysis.

8.4.2 Dana analyses

The intra-session reliability of each variation-load-hand combination was determined by intraclass correlation coefficients with their 95 % confidential intervals, using the software package R, version 3.5.2 (The R Foundation for Statistical Computing, Vienna, Austria). The magnitude of intraclass correlation coefficient was interpreted as follows: < 0.50, poor reliability; 0.50 to 0.75, moderate reliability; 0.75 to 0.90, good reliability; and > 0.90, excellent reliability (Koo & Li, 2016). The relationship between PV and the prescribed loads was established via a linear regression, using Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA).

Data are presented as means and standard deviations. Individual 2(hand [dominant and non-dominant hand])*3(variation [LPwo, LPw, and LP]) repeated measures ANOVA with Bonferroni post-hoc test was applied to compare the slope and intercept of the regression lines of each variation and hand. Lastly, individual 2(hand [dominant and non-dominant hand])*3(variation [LPwo, LPw, and LP])*3(load [20, 22.5, and 25 kg]) repeated measures ANOVA with Bonferroni post-hoc test was also applied to compare the PV attained at each variation, hand, and load. Statistical significance was set at an alpha level of $p < 0.05$, whereas this part of statistical analyses was performed using the software package SPSS (version 28.0.1.0: SPSS, Inc., Chicago, IL). Cohens' d effect sizes with 95% confidence intervals were used to determine the magnitude of the difference between LPwo, LPw, and LP for the slope and intercept of linear regression and were interpreted as: small, $d = 0.20$; medium, $d = 0.50$; and large, $d = 0.80$ (Hedges & Olkin, 2014).

8.5 Results

The reliability results of each variation-load-hand combination are shown in Table 10. Most variations displayed excellent reliability (ICC > 0.91), especially for the NH (ICC = 0.92 to 0.97) with a few demonstrating good reliability (ICC = 0.77 to 0.78) for the DH. In general, the variations performed with the NH were as reliable, or more reliable, than with the DH.

Table 10. Reliability of each variation-load-hand combination of landmine punch throw.

CONDITION	DOMINANT HAND			NON-DOMINANT HAND		
	ICC	LCI	UCI	ICC	LCI	UCI
LP 20 kg	0.89	0.75	0.96	0.93	0.84	0.97
LP 22.5 kg	0.94	0.85	0.98	0.94	0.84	0.98
LP 25 kg	0.77	0.54	0.91	0.89	0.76	0.96
LPw 20 kg	0.88	0.75	0.96	0.89	0.77	0.96
LPw 22.5 kg	0.82	0.63	0.93	0.95	0.89	0.98
LPw 25 kg	0.93	0.84	0.97	0.92	0.81	0.97
LPwo 20 kg	0.87	0.72	0.95	0.94	0.87	0.98
LPwo 22.5 kg	0.95	0.89	0.98	0.92	0.83	0.97
LPwo 25 kg	0.78	0.55	0.92	0.97	0.94	0.99

LP = landmine punch throw; LPw = landmine punch throw with the rotation of trunk; LPwo = landmine punch throw without rotation; ICC = intraclass correlation; LCI = lower confidence interval; UCI = upper confidence interval.

Very strong linear relationships were observed for group averages for LPwo, LPw, and LP performed by DH ($R^2 = 0.96$, $R^2 = 0.99$, and $R^2 = 0.99$), and NH for each variation ($R^2 = 0.99$).

The slopes of the linear regression with their effect size are shown in Table 11. The two-way repeated measures ANOVA indicated that there was no variation*hand interaction for the slope of regression lines ($p = 0.212$), and there was no main effect for variation ($p = 0.118$) or hand ($p = 0.539$).

Table 11. Results of the slope of linear regression with their standard deviation.

CONDITION	DOMINANT HAND	NON-DOMINANT	COHEN'S D (95% CI)
SLOPE OF LINEAR REGRESSION			
LP	-0.06 ± 0.05	-0.05 ± 0.04	0.22 [-0.53 to 0.96)]
LPw	-0.08 ± 0.04	-0.07 ± 0.02	0.32 [-0.44 to 1.05)]
LPwo	-0.07 ± 0.02	-0.08 ± 0.02	0.50 [-0.27 to 1.24)]
INTERCEPT OF LINEAR REGRESSION			
LP	3.88 ± 1.00	3.56 ± 0.93	0.33 [-0.43 to 1.06]
LPw	3.54 ± 0.69	3.35 ± 0.37	0.34 [-0.41 to 1.08]
LPwo	3.07 ± 0.40	3.32 ± 0.46	-0.59 [-1.32 to 0.19]

LP = landmine punch throw; LPw = landmine punch throw with the rotation of trunk; LPwo = landmine punch throw without rotation; CI = 95% confidence intervals.

The intercepts of the linear regression with their effect sizes are shown in Table 11. The two-way repeated measures ANOVA indicated that there was no variation*hand interaction for the intercept of regression lines (p = 0.146), and there was no main effect for variation (p = 0.092) or hand (p = 0.781).

Additionally, there were no variation*hand*load, variation*hand, variation*load, or hand*load interactions for PV (p = 0.148, p = 0.920, p = 0.086, p = 0.718), respectively. However, there was main effect for variation, load, and hand (p < 0.001, p < 0.001, p = 0.006), respectively. Post-hoc testing showed that the PV of LP (2.47 ± 0.34 m/s) was greater than LPw (1.80 ± 0.24 m/s; p < 0.001) and LPwo (1.52 ± 0.26 m/s; p < 0.001), and PV of LPw was less than LPwo (p < 0.001). Additionally, PV was greater with 20 kg (2.10 ± 0.44 m/s) than 22.5 kg (1.93 ± 0.47 m/s, p < 0.001) and 25 kg (1.76 ± 0.49 m/s, p < 0.001), and PV of 22.5 kg was greater than 25 kg (p < 0.001). Lastly, the PV was greater with DH (1.98 ± 0.48 m/s) than NH (1.88 ± 0.49 m/s; p = 0.006). The PVs attained against each load, variation, and hand with their effect size are shown in Table 12.

Table 12. Peak velocities (m/s; mean ± SD) attained against each load between the landmine punch throw variations performed with the dominant and non-dominant hands.

CONDITION	DOMINANT HAND	NON-DOMINANT	COHEN'S D (95% CI)
LP 20 kg	2.66 ± 0.32	2.54 ± 0.36	0.35 (-0.40 to 1.09)
LP 22.5 kg	2.53 ± 0.31	2.43 ± 0.34	0.31 (-0.45 to 1.04)
LP 25 kg	2.36 ± 0.34	2.28 ± 0.32	0.24 (-0.51 to 0.98)
LPw 20 kg	2.03 ± 0.14	1.94 ± 0.18	0.56 (-0.21 to 1.30)
LPw 22.5 kg	1.85 ± 0.17	1.74 ± 0.20	0.59 (-0.18 to 1.33)
LPw 25 kg	1.65 ± 0.24	1.58 ± 0.22	0.20 (-0.45 to 1.04)
LPwo 20 kg	1.75 ± 0.19	1.68 ± 0.23	0.33 (-0.42 to 1.07)
LPwo 22.5 kg	1.53 ± 0.20	1.49 ± 0.23	0.19 (-0.56 to 0.92)
LPwo 25 kg	1.42 ± 0.18	1.27 ± 0.24	0.71 (-0.08 to 1.45)

LP = landmine punch throw; LPw = landmine punch throw with the rotation of trunk; LPwo = landmine punch throw without rotation; CI = 95% confidence intervals.

8.6 Discussion

In the current study, the main findings are that: (I) the variation, hand, and load influence the PV achieved; (II) all possible combinations of the landmine punch throw were reliable in this study (ICC = 0.77 to 0.97), no matter the variation, load, or hand; (III) the goodness of fit were similar for the group average for each variation of landmine punch throw for both the DH and NH; the hand and variation of landmine punch throw have not effect on the slope, and the intercept of regression line. Although, some studies have determined the load-velocity reliability of upper-body bilateral pushing exercise (García-Ramos et al., 2015; García-Ramos et al., 2018a; García-Ramos et al., 2021b) to the best author knowledge, this is the first study to determine the reliability of upper-body unilateral exercises that can be used for field testing and monitoring.

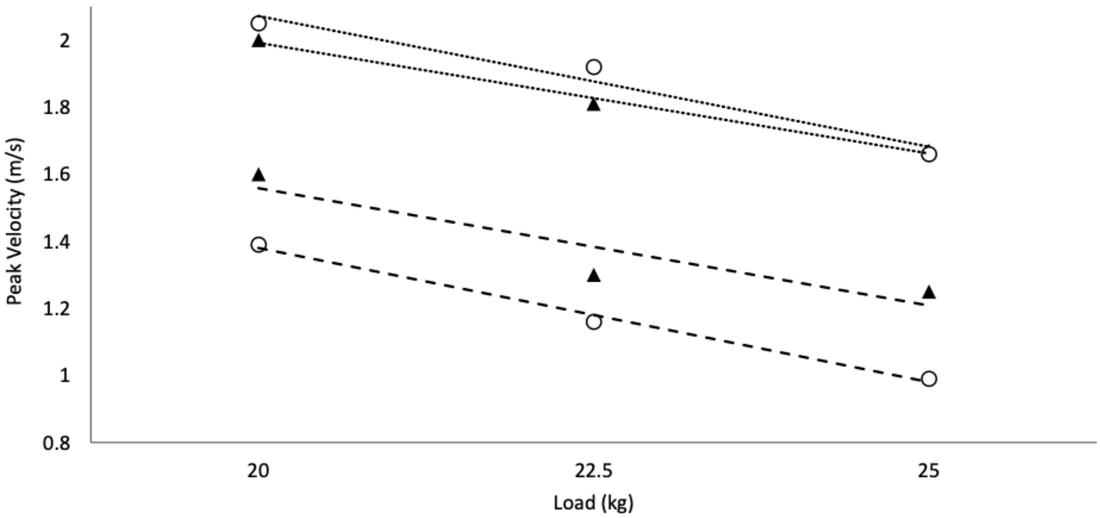
There were not any variation*hand*load, variation*hand, variation*load, or hand*load interactions for PV. However, there were main effects of variation, load, and hand, meaning that PV was affected by each of these factors independently. For example, as expected, the more body segments that were involved in the LPT, the greater the resultant PV was in the present study. In a similar fashion, others have found the same pattern during punching with the whole body, with the legs fixed, and with legs and trunk fixed (Gu et al., 2018). Another expected outcome was that PV decreased as the load increased, which abides by the inverse load-velocity relationship (Bosquet et al., 2010; González-Badillo & Sánchez-Medina, 2011; Jukic et al., 2020b). Additionally, PV was greater with the dominant hand compared to non-dominant hand, which is similar to previous research assessing punch velocity (López-Laval et al., 2020). Although these findings were all expected, they provide the foundation from which the remainder of the discussion is built upon.

In this study, all possible combinations of the landmine punch throw were reliable (ICC = 0.77 to 0.97), regardless of the variation, load, or hand, meaning that all of the different landmine punch throws performed could be used in practice. However, it was interesting that trials performed with the non-dominant hand were more reliable than those performed with the dominant hand. This may have occurred because PV was greater with the dominant hand, indicating that perhaps the fastest dominant hand trial may have been performed with greater PV than the other repetitions, with the non-dominant hand moving at a slower speed but more consistently. In support of this idea, previous research showed similar results for peak force in trained boxers, where the non-dominant hand was more reliable (ICC = 0.89) than the dominant hand (ICC = 0.73) (Lenetsky et al., 2018). In a real-life boxing bout, boxers most often perform straight punches with their lead hand, which is often the non-dominant hand (Davis et al., 2013, 2018), which might influence the lower variability of the non-dominant hand and reflect greater within-session reliability of non-dominant compared to dominant hand straight punches (Lenetsky et al., 2018). Considering that the landmine punch throw used in this study was performed in different variations, with the dominant and non-dominant hand, and with different loads, it seems that each of those variations could be used as a reliable unilateral ballistic test as part of an upper-body force velocity profile (García-Ramos, et al., 2021a; Pérez-Castilla et al., 2020; Ruf et al., 2018).

Each landmine punch throw variation performed with the DH and NH had a very strong linear relationship with the slopes of the regression lines which were not affected by hand or variation. In a previous study (Balsalobre-Fernández et al., 2019), the slopes of the regression lines in bilateral and unilateral knee extensions were similar to those of the present study, but that study did not indicate whether differences existed between bilateral and unilateral knee extensions or between the dominant and non-dominant leg. In resistance training exercises, the velocity typically demonstrates a linear decrease as the load increases (Ruf et al., 2018). This inverse relationship between velocity and load is an important factor in understanding an individual's performance. However, the intercept, which represents the baseline velocity when the load is zero, can also provide valuable information about a person's performance (Samozino et al., 2014). Analyzing both the velocity-load relationship and the intercept can help to develop a comprehensive understanding of an individual's performance capabilities in resistance training exercises. In our study, the intercept of the regression lines were not affected by hand or variation, but in aforementioned study, the intercept of thee regression line was significantly different between the bilateral and unilateral knee extension.

Additionally, the load-velocity relationship has been explored for a wide range of exercises such as the bench press throw (García-Ramos et al., 2018b), deadlift (Jukic et al., 2020b, 2020c), back squat (Thompson et al., 2021), and others (Balsalobre-Fernández et al., 2018; Kotani et al., 2022). However, no previous research has compared the linearity of the load-velocity relationship for an upper-body unilateral ballistic exercise. Our results provided a fairly linear velocity relationship (R2 ≥ 0.96), similar to the bench press throw (R2 = 0.979) (García-Ramos et al., 2018b), which is commonly used as an upper-body unilateral ballistic test. However, bilateral testing cannot observe the asymmetry of the upper-body, which makes the landmine punch throw an interesting option for athletes that perform sport actions one limb at a time. For example, two individual sets of data from the current study (Figure 2) show distinct differences between limbs within one fairly untrained subject while a well-trained subject displayed little-to-no between-limb asymmetry. Therefore, considering the findings of this paper, in addition to the data in Figure 2, using a unilateral test could help identify asymmetries that could not be identified using a bilateral test. Furthermore, putting asymmetries aside, the landmine punch throw also can be used to track an individual's progress over time thanks to its reliability, linearity, and goodness of fit. Thus, using this upper-body unilateral ballistic exercise could be suitable for different sports discipline where the movement is commonly performed unilaterally, such as punching or throwing.

Figure 15. An example of the load-velocity profile for landmine punch throw without rotation for a fairly untrained and well-trained subject



Dotted line = well-trained subject; Dashed line = fairly untrained subject; Point = non-dominant hand; Triangle = dominant hand

8.7 Practical application

The landmine punch throw can be used as a reliable upper-body unilateral ballistic test for athletes. By performing the test with the dominant and non-dominant hand with different loads (20, 22.5, and 25 kg), the different landmine punch throw variations assessed in this study can all be used to create upper-body unilateral load-velocity profiles. However, as with other exercises like the back squat, bench press, etc., the group's average results should not be used as a benchmark for each athlete, which requires load-velocity profiles to be compared within each athlete individually.

9 Overall conclusion

Athletes of many sports can use different devices that provide instantaneous feedback that can be used for monitoring and testing performance. For example, global positioning systems monitor players' running parameters such as speed and distance covered during football training, force plates can monitor basketball players' jump parameters such as height and peak velocity, and linear position transducers can monitor athletes' lifting velocity during strength and conditioning sessions, etc. However, not every sport discipline has devices that were innovated for their specific purpose.

As the beginning of my PhD journey in 2018, one type of sport that had recently received its own performance monitoring devices was combat sports, or more specifically, boxing. At that time, a few commercially available devices were released on the market and claimed to be able to detect and recognize different punch types in order to quantify the number of punches thrown during a session, allowing for performance measures of those punches (e.g., velocity) to be assessed. However, although they were being sold and used in practice, no study has assessed the validation of those punch trackers.

Firstly, for a device to be able to provide performance metric of individual punches, it must first be able to detect and recognize each punch correctly, regardless of the punch type, the technique or training level of the fighters, the order of the punches, etc. Therefore, the purpose of the first study included in this dissertation was simply to determine whether or not punch trackers could detect and recognize punches. In the end, not every punch tracker could be included in the final data analyses because the StrikeTec punch tracker was excluded due to technical failures and missing data sets from some participants. Therefore, only three punch trackers were included for the final analysis: Corner, Hykso, and Everlast. The main findings showed that those punch trackers detected the punch types with greater accuracy in trained punchers compared to untrained punchers. Further, straight punches were better detected than uppercuts and hooks. However, not every punch tracker allowed for punch-by-punch analyses (the Everlast punch tracker provided only a summary of the session, thereby excluding it for further data analysis). With the corner and Hykso punch trackers remaining, the correct recognition of punch type was affected by the position of the punch in sequence, as earlier punches were recognized better than latter punches. Therefore, the overall conclusion of the first study was that the Corner and Hykso punch trackers seem to be most valid punch trackers for detecting, recognizing, and counting punches.

Nevertheless, although athletes would be interested in punch type and punch count data, they would likely also be interested in performance metrics like punch velocity and the like. Therefore, the purpose of the next study was to determine the validity of commercially available punch trackers to provide valid punch velocity and punch force data. As with the previous study, the Everlast punch tracker was not included because it did not allow for punch-by-punch analyses. To complicate matters, not every punch tracker provided detailed information regarding the exact units of measurement for their variables. Therefore, various punch tracker variables were compared against the peak and mean velocity provided by an optical 3-dimensional motion capture system and force obtained from a wall-mounted force plate. The main findings of that study were that none of the punch trackers strongly correlated with the gold standard data and the percentage error was significantly affected by punch type. However, contrary to the previous study where training experienced played a role in the resultant data, it did not affect the percentage error in this study. In addition, for peak velocity, the percentage error was affected by punch intensity, indicating that some variables from some punch trackers were quantified differently when punches were performed at 50% or 100% of max effort. Therefore, this study indicated that Hykso and Corner could be used for monitoring peak velocity, if the error of accuracy will be accepted. However, based on the previous two studies combined, it seems like the commercially available punch trackers should not be used to provide research-grade data in the future (unless changes are made to the software, hardware, etc., that would increase the validity of those devices).

Despite the relatively poor scientific data, users will likely continue to use these devices. Therefore, the results from those two studies can help potential users choose which punch tracker can be used for the sport-specific testing of boxers performance such as the shadow boxing and boxing with an impact, when the coaches aim to monitor and test a boxers ability during the real-life conditions. However, from practical point of view, punch trackers that do not allow for punch-by-punch data are limited for monitoring boxing sessions. Although, if punch tracker technology improves, they could be quite useful for assessing which punch types a boxer should work on regarding their punch selection, technique, execution, speed, force, etc.

After realizing that punch trackers could not be used in research settings to quantify punch data, my ideas about quantifying and assessing training shifted a bit. Around the same time, the landmine punch throw exercise began to gain popularity as a ballistic unilateral upper body exercise. As the landmine punch throw could be used as a movement-specific test for many upper body sport skills (including throwing, pushing, punching, etc.), the next logical step of my dissertation investigations was to determine its reliability.

As no study had investigated the reliability of the landmine punch throw, the purpose of my final study was to determine the reliability of multiple commonly-used landmine punch throw variations and to assess them at different loads. The results of this study showed that all of the landmine punch throw loads and variations were reliable for both the dominant and non-dominant hand, with the non-dominant hand even being more reliable. Therefore, from practical point of view the landmine punch throw could be used as a reliable specific-movement test for upper-body ballistic strength and power. Additionally, since we used multiple loads, we were able to create load-velocity profiles for each hand and each variation for all of the boxers. As a group, the load-velocity profiles displayed a strong linear relationship, but regardless of the group averages, it is important to look at the data for each individual. In particular, some less-experienced boxers showed load-velocity profiles that heavily favored one hand over the other, whereas others displayed a flat line, indicating that they likely need to adjust their training to focus on maximizing movement speed or force, depending on their profile. Moreover, it is important to consider that landmine punch throw could be used for wide range of sports disciplines, not only for boxing. Regardless of the sport, the landmine punch throw could be an important movement to not only assess, but also to improve hand velocity.

In conclusion, during my PhD, I had the honor to cooperate with many successful researchers and coaches from around the country and abroad, which gave me an opportunity to learn from experts in sport science. I learned how to critically think about research problems, search for mutual connections between phenomena, create arguments pro and con, understand research articles, and search for “gaps” in a specific field which I was interested in at that time. Based on that, I learned how to prepare a research study and identify potentional critical situations which could devaluate research. Following the whole process since start till successfully publishing manuscript, with sometimes, from my point of view never ending responding to reviewers. Further, my PhD taught me how to a lead students during their final theses and provide them suitable advice to successfully defend their thesis. Lastly, an opportunity to be at Sheffield Hallam University on my compulsory internship provided me memorable experiences, new colleagues, and cooperation on one of the main parts of my dissertation.

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List of attachments

Appendix 1: The original of the confirmed form by the Ethical Committee of Charles University FTVS

UNIVERZITA KARLOVA
FAKULTA TĚLESNÉ VÝCHOVY A SPORTU
José Martího 31, 162 52 Praha 6-Veleslavín

Žádost o vyjádření Etické komise UK FTVS

k projektu výzkumné, kvalifikační či seminární práce zahrnující lidské účastníky

Název projektu: Validační studie boxerských akcelerometrů

Forma projektu: výzkumná práce – doktorská práce

Období realizace: květen 2019 – červenec 2019

Předkladatel: Mgr. Dan Omcirk, UK FTVS, Katedra fyziologie a biochemie

Hlavní řešitel: Mgr. Dan Omcirk, UK FTVS, Katedra fyziologie a biochemie

Místo výzkumu (pracoviště): UK FTVS, Katedra fyziologie a biochemie, laboratoř LE3-2

Vedoucí práce (v případě studentské práce): James J. Tufano, Ph.D.

Popis projektu: Cílem výzkumu bude komparace boxerských akcelerometrů, které měří rychlost, zrychlení a sílu při provádění boxerského úderu (Hykso, Everlast, StrikeTec, Corner) a ActiGraphu, který monitoruje pohyb těla, popřípadě pohyb končetiny při pohybových aktivitách. Probandi budou provádět řadu boxerských kombinací, která budou v náhodném pořadí. Údery budou prováděny proti boxerskému aparátu Loadstar, který zaznamenává rychlost a sílu boxerských úderů. Pro potřeby výzkumu bude také využito zařízení snímající kinematiku pohybu Qualisys track manager. Pro zjištění tělesné kompozice bude využit přístroj In-Body.
Proband před měřením provede standardizované rozcvičení a poté řadu boxerských kombinací, které budou dohromady obsahovat 100 úderů (přední údery, „háky" a „zvedáky" pravou i levou horní končetinou) bez kontaktu se silovou deskou (stínový box – box bez kontaktu se soupeřem). Mezi každou kombinací bude doba odpočinku 3 až 5 vteřin.
V průběhu tohoto stínového boxu bude mít proband boxerské rukavice o hmotnosti 280g (10 uncí). Pod boxerskou rukavicí budou uchyceny všechny 4 boxerské akcelerometry a ActiGraph.
Další testováním bude provádění boxerských úderů s kontaktem se silovou deskou. Proband bude mít připevněny markery pro analýzu rychlosti a síly pohybu a akcelerometry společně s ActiGraphem, stejně jako v průběhu předchozího testování. Bude provedeno dohromady 30 jednotlivých úderů na silovou desku s intenzitou přibližně 50% individuálního maxima a 30 jednotlivých úderů s maximální intenzitou (5 přímých úderů, 5 „háků" a 5 „zvedáků", pokaždé levou i pravou horní končetinou). Doba odpočinku bude přibližně 5 až 10 vteřin.
Veškeré testování jednoho probanda proběhne v jeden den a časovém rozmezí 30 až 60 minut.
Charakteristika účastníků výzkumu: Předpokládaný počet účastníků bude dohromady 60 jedinců (30 studentů UK FTVS a 30 aktivních boxerů). Věkové rozhraní výzkumné souboru bude 18 – 40 let. Předpokladem pro účasti na výzkumu bude platná zdravotní prohlídka, která umožňuje provádět aktivity se zvýšenou fyzickou zátěží. Do výzkumu nebudou zařazeni jednotlivci se zdravotními problémy, které by znemožňovaly realizaci výzkumu, nebo by jakýmkoliv způsobem probanda ohrožovaly na zdraví. Probandi budou instruováni ohledně techniky provádění jednotlivých boxerských úderů. Samotnému měření bude předcházet teoretické seznámení se správnou technikou úderů a následovat bude praktická část, aby nedošlo k nežádoucímu zranění.
Účastníky výzkumu vybere hlavní řešitel projektu Mgr. Dan Omcirk, popřípadě po konzultaci s lékařem MUDr. Ing. Tomášem Větrovským, Ph.D.
Zajištění bezpečnosti: V průběhu testování budou využity neinvazivní metody (měření tělesného složení a kombinace boxerských úderů). Rizika prováděného testování nebudou vyšší než běžně očekávaná rizika u tohoto typu testování. Každé návštěvě bude předcházet standardizované rozcvičení, které by mělo zamezit nežádoucímu zranění probandů. Bude se jednat o rozcvičení převážně horní končetin, mobilizační a tonizační cvičení. Testování probandů bude provádět Mgr. Dan Omcirk za pomoci proškolených pracovníků: James J. Tufano, Ph.D., MUDr. Ing. Tomáš Větrovský, Ph.D., Mgr. Jan Maleček, Ing. Petr Kubový, Bc. Jan Pádecký.
Etické aspekty výzkumu: Účast na výzkumu bude zcela dobrovolná. Bude se jednat o zletilé jedince se zdravotní způsobilostí pro realizace výzkumu. Veškerá získaná data budou zpracována a bezpečně uchována v anonymní podobě a publikována ve výzkumné práci, popřípadě v odborných časopisech, monografií a prezentována na konferencích, popřípadě budou využita při další výzkumné práce na UK FTVS. Po anonymizaci budou osobní data smazána. Anonymizace osob na fotografiích bude provedena začerněním/rozmazáním obličejů či částí těla, znaků, které by mohly vést k identifikaci jedince. Videozáznam bude přístupný pouze hlavnímu řešiteli, který bude videozáznam nahrávat. Veškeré neanonymizované fotografie a videozáznamy budou uchovány na heslem zajištěném počítači výzkumníka a po výzkumu budou všechny neanonymizované fotografie a videozáznamy výzkumníkem smazány.
V maximální možné míře zajistím, aby získaná data nebyla zneužita.
Text informovaného souhlasu: přiložen

Povinností **všech účastníků výzkumu na straně řešitele** je chránit život, zdraví, důstojnost, integritu, právo na sebeurčení, soukromí a osobní data zkoumaných subjektů, a podniknout k tomu veškerá preventivní opatření. Odpovědnost za ochranu zkoumaných subjektů leží vždy na účastnících výzkumu na straně řešitele, nikdy na zkoumaných, byť dali svůj souhlas k účasti na výzkumu. Všichni účastníci výzkumu na straně řešitele musí brát v potaz etické, právní a regulační normy a standardy výzkumu na lidských subjektech, které platí v České republice, stejně jako ty, jež platí mezinárodně.

UNIVERZITA KARLOVA
FAKULTA TĚLESNÉ VÝCHOVY A SPORTU
José Martího 31, 162 52 Praha 6-Veleslavín

Potvrzuji, že tento popis projektu odpovídá návrhu realizace projektu a že při jakékoli změně projektu, zejména použitých metod, zašlu Etické komisi UK FTVS revidovanou žádost.

V Praze dne: 15. 5. 2019

Podpis předkladatele:

Vyjádření Etické komise UK FTVS

Složení komise: **Předsedkyně:** doc. PhDr. Irena Parry Martínková, Ph.D.
Členové: prof. PhDr. Pavel Slepička, DrSc.
doc. MUDr. Jan Heller, CSc.
PhDr. Pavel Hráský, Ph.D.
Mgr. Eva Prokešová, Ph.D.
MUDr. Simona Majorová

Projekt práce byl schválen Etickou komisí UK FTVS pod jednacím číslem: 127/2019

dne: 16. 5. 2019

Etická komise UK FTVS zhodnotila předložený projekt a **neshledala žádné rozpory** s platnými zásadami, předpisy a mezinárodní směrnicemi pro provádění výzkumu zahrnujícího lidské účastníky.

Řešitel projektu splnil podmínky nutné k získání souhlasu Etické komise.

UNIVERZITA KARLOVA
Fakulta tělesné výchovy a sportu
José Martího 31, 162 52, Praha 6
– 20 –

razítko UK FTVS

podpis předsedkyně EK UK FTVS

Appendix 2: An institutional review board-approved informed consent document

INFORMOVANÝ SOUHLAS

Vážený pane, vážená paní,

v souladu se Všeobecnou deklarací lidských práv, zákonem č. 101/2000 Sb., o ochraně osobních údajů a o změně některých zákonů, ve znění pozdějších předpisů a dalšími obecně závaznými právními předpisy *(jakož jsou zejména Helsinská deklarace, přijatá 18. Světovým zdravotnickým shromážděním v roce 1964 ve znění pozdějších změn (Fortaleza, Brazílie, 2013); Zákon o zdravotních službách a podmínkách jejich poskytování (zejména ustanovení § 28 odst. 1 zákona č. 372/2011 Sb.) a Úmluva o lidských právech a biomedicíně č. 96/2001, jsou-li aplikovatelné),* Vás žádám o souhlas s Vaší účastí ve výzkumném projektu v rámci disertační práce na UK FTVS s názvem Validační studie boxerských akcelerometrů prováděné na Katedře fyziologie a biochemie v laboratoři LE3-2.
Pro potřeby výzkumu není využito žádných finančních prostředků z grantových agentur. Cílem výzkumu bude komparace boxerských akcelerometrů, které měří rychlost, zrychlení a sílu při provádění boxerského úderu (Hykso, Everlast, StrikeTec, Corner) a ActiGraphu, který monitoruje pohyb těla, popřípadě pohyb končetiny při pohybových aktivitách. Budete provádět řadu boxerských kombinací, která budou v náhodném pořadí. Údery budou prováděny proti boxerskému aparátu Loadstar, který zaznamenává rychlost a sílu boxerských úderů. Pro potřeby výzkumu bude také využito zařízení snímající kinematiku pohybu Qualisys track manager. Pro zjištění tělesné kompozice bude využit přístroj In-Body.
Budete instruováni ohledně techniky provádění jednotlivých boxerských úderů. Samotnému měření bude předcházet teoretické seznámení se správnou technikou úderů a následovat bude praktická část, aby nedošlo k nežádoucímu zranění. V rámci návštěvy provedete standardizované rozcvičení, po kterém bude následovat řada boxerských kombinací ve stínovém boxu (celkový počet úderů bude 100). Mezi každou sérií úderů bude doba odpočinku v časovém rozmezí 3 až 5 vteřin. Kombinace úderů budete provádět s boxerskými rukavicemi o hmotnosti 10-ti uncí (280g). Pod boxerskou rukavicí budou upevněny všechny 4 boxerské akcelerometry a ActiGraph. Po ukončení boxerských kombinací provedete dohromady 60 úderů na silovou desku Loadstar (30 úderů s 50% intenzitou individuálního maxima a 30 úderů s maximální intenzitou). V obou případech se bude jednat o 5 přímých úderů („direktů“), 5 „háků“ a 5 „zvedáků“. Údery provedete levou i pravou horní končetinou. Stejně jako v při předchozím stínovém boxu, budete mít upevněny akcelerometry a ActiGraph pod boxerskou rukavicí. Pro analýzu rychlosti a síly pohybu budou na rukavici upevněny markery. Doba odpočinku mezi jednotlivými údery bude přibližně 5 až 20 vteřin. Každé návštěvě bude předcházet standardizované rozcvičení, které by mělo zamezit nežádoucímu zranění probandů. Bude se jednat o rozcvičení převážně horní končetin, mobilizační a tonizační cvičení.
V průběhu testování budou využity neinvazivní metody (měření tělesného složení a kombinace boxerských úderů).
Veškeré testování proběhne v jeden den a časovém rozmezí 30 až 60 minut. Dohromady provedete 160 boxerských úderů v náhodném pořadí, které bude předem randomizováno. Testování probandů bude provádět Mgr. Dan Omcirk za pomoci proškolených pracovníků: James J. Tufano, Ph.D., MUDr. Ing. Tomáš Větrovský, Ph.D., Mgr. Jan Maleček, Ing. Petr Kubový, Bc. Jan Pádecký.
Rizika prováděného testování nebudou vyšší než běžně očekávaná rizika u tohoto typu testování.

Do projektu nemůže být zařazen proband, který bude mít zranění či akutní onemocnění nebo proband s jakýmkoliv onemocněním či omezením pohybového aparátu nebo rekonvalescenci po onemocnění či úrazu.
Výsledky výzkumu napomohou k odhalení možnosti využití akcelerometrů v boxerském tréninku, které mohou využívat jak profesionální, tak amatérští boxeři, popřípadě širší veřejnost.
Veškeré testování je dobrovolné a bezplatné, bez nároku na finanční odměnu.
Veškerá získaná data budou zpracována a bezpečně uchována v anonymní podobě a publikována ve výzkumné práci, popřípadě v odborných časopisech, monografií a prezentována na konferencích, popřípadě budou využita při další výzkumné práce na UK FTVS. Po anonymizaci budou osobní data smazána. Anonymizace osob na fotografiích bude provedena začerněním/rozmazáním obličejů či částí těla, znaků, které by mohly vést k identifikaci jedince. Videozáznam bude přístupný pouze hlavnímu řešiteli Veškeré neanonymizované fotografie a videozáznamy budou uchovány na heslem zajištěném počítači výzkumníka a po výzkumu budou všechny neanonymizované fotografie a videozáznamy výzkumníkem smazány.
V maximální možné míře zajistím, aby získaná data nebyla zneužita.
Výsledky testování Vám budou poskytnuty v případě zájmu okamžitě po absolvování jednotlivých testů u vedoucího výzkumného projektu – Dana Omcirka.
Jméno a příjmení předkladatele a hlavního řešitele projektu Mgr. Dan Omcirk
Jméno a příjmení osoby, která provedla poučení:
Mgr. Dan Omcirk Podpis:...................………..
Prohlašuji a svým níže uvedeným vlastnoručním podpisem potvrzuji, že dobrovolně souhlasím s účastí ve výše uvedeném projektu a že jsem měl(a) možnost si řádně a v dostatečném čase zvážit všechny relevantní informace o výzkumu, zeptat se na vše podstatné týkající se účasti ve výzkumu a že jsem dostal(a) jasné a srozumitelné odpovědi na své dotazy. Potvrzuji, že mám platnou zdravotní prohlídku. **Potvrzuji, že mám platnou zdravotní prohlídku.** Byl(a) jsem poučen(a) o právu odmítnout účast ve výzkumném projektu nebo svůj souhlas kdykoli odvolat bez represí, a to písemně Etické komisi UK FTVS, která bude následně informovat předkladatele projektu.

Místo, datum ....
Jméno a příjmení účastníka .... Podpis: ....

Appendix 3: An institutional review board-approved informed consent document

Validation of a Landmine Punch Throw Profile
Ethics Review ID: ER19357858
Workflow Status: Application Approved
Type of Ethics Review Template: All other research with human participants
Primary Researcher / Principal Investigator
Alan Ruddock
(Centre for Sport and Exercise Science)
Converis Project Application: Q1. Is this project i) Staff research
Other SHU Investigator
Stephen Thompson
(Centre for Sport and Exercise Science)
Q3b. External Investigator Details: Dan Omcirk - Charles University (Prague) Dr James Tufano - Charles University (Prague)
Q4. Proposed Start Date of Data Collection: 18/11/2019 **Q5. Proposed End Date of Data Collection :** 28/02/2020
Q6. Will the research involve any of the following
i) Participants under 5 years old: No
ii) Pregnant women: No
iii) 5000 or more participants: No
iv) Research being conducted in an overseas country: No **Q7. If overseas, specify the location:**
Q8. Is the research externally funded?: No
Q9. Will the research be conducted with partners and subcontractors?: No
Q10. Does the research involve one or more of the following?
i. Patients recruited because of their past or present use of the NHS or Social Care: No
ii. Relatives/carers of patients recruited because of their past or present use of the NHS or Social Care: No
iii. Access to data, organs, or other bodily material of past or present NHS patients: No
iv. Foetal material and IVF involving NHS patients: No
v. The recently dead in NHS premises: No
vi. Participants who are unable to provide informed consent due to their incapacity even if the project is not health related: No
vii. Prisoners or others within the criminal justice system recruited for health-related research: No **viii. Prisoners or others within the criminal justice system recruited for non-health-related research:** No
ix. Police, court officials or others within the criminal justice system: No
Q11. Category of academic discipline: Physical Sciences and Engineering **Q12. Methodology:** Quantitative
P2 - Project Outline

Q1. General overview of study: We have recently developed a method for profiling an athletes barbell velocity in a punch specific manner, using an upright barbell throw. In this test, a barbell is inserted vertically into an attachment (landmine attachment) so it is free to move around in all planes of motion. The athlete takes the bar in the rear hand

stance and throws the bar with maximum effort to the receiver. The bar speed is assessed using a linear position transducer (Gymaware, AUS). The load on the bar is increased from
20 kg (bar only), in 5 kg increments to 40 kg and each time indices of velocity are recorded at each load to create a load-velocity profile in a punch specific movement pattern.
This method is a whole-body assessment and in this study we would like to seperate this action to isolate the lower body and rotational aspects. Therefore we would like to investigate:
1) Upper body punch throw no rotation
2) Upper body punch throw with rotation
3) Landmine punch throw test
Using this method we would like to investigate the effect of the upper body and torque generating capability of the trunk to the landmine punch throw test as well as investigate the relationship between these tests and common physical tests such as jumping and body composition.
Q2. Background to the study and scientific rationale (if you have already written a research proposal, e.g. for a funder, you can upload that instead of completing this section).: Punch-speed is approximately 8.9 m/s, meaning that strength and acceleration are extremely important (Obmi#ski, Blach, 2012; Pierce, Reinbold, Lyngard et al., 2006; Šiška et al., 2016). Strength training should be complemented with exercises to increase the force-velocity spectrum of athletes performance (Bogdanis et al., 2018). To increase muscle strength, high resistance training is used. High resistance may also affect muscular hypertrophy. It may be unwarranted in weight-division sports such as boxing. Therefore, boxers may wish
to complete low volumes, high-speed strength training to reap the neuromuscular benefits, but avoid the hypertrophic effects (Lahart, Robertson, 2009). To achieve this, boxers can perform medicine ball throws, plyometric push-ups and different kind of exercise which are similar as a boxing punch, as a landmine punch etc. Where they focus on the speed of their movement rather than external resistance. Loturco et al. (2019), investigated transfer from short-term high-velocity training program to the punch characteristics. The results of the study indicated that the impact of a boxing punch could be influenced by short-term explosive training. However, at present, there are few assessments that are able to profile changes in explosive force capabilities in combat sports. Therefore, this piece of research will investigate the validity of three types
of landmine punch throw test to provide a basis for future assessments of punch specific performance in response to training.
Q3. Is your topic of a sensitive/contentious nature or could your funder be considered controversial?: No
Q4. Are you likely to be generating potentially security-sensitive data that might need particularly secure storage?: No
Q5. Has the scientific/scholarly basis of this research been approved, for example by Research Degrees Sub-committee or an external funding body?: Yes
Q6. Main research questions: 1) What is the difference in mean and peak velocity between
a) Upper body punch throw no rotation b) Upper body punch throw with rotation c) Landmine punch throw test
2) What is the relationship between a) punch throw with no rotation and landmine punch throw and b) punch throw with rotation and landmine punch throw

3) What is the relationship between landmine punch throw tests and countermovement jump, squat jump and body composition (skeletal muscle mass, body fat mass etc.)
Q7. Summary of methods including proposed data analyses: Participants will visit the laboratory on two occasions one week apart.
In a counter-balanced order participants will undertake in the following order:
Visit 1:
a) Body composition assessment
b) Squat jump (5 jumps with 30 s rest)
c) Countermovement jump (5 jumps with 30 s rest)
d) In a randomised order either: Upper body punch throw no rotation, Upper body punch throw with rotation, landmine punch throw. (3 reps at each load, 2 min rest between each load).
In the punch throw tests mass will be added to the barbell in increments of either 2.5 kg or 5 kg until a maximum of 40 kg is loaded on the bar.
Visit 2:
Repeat on punch throw tests in a randomised counter-balanced order.
Data analysis:
Assumptions for parametric statistical analysis (e.g. normality, homegeneity of variance etc.) Two-Way Repeated Measures ANOVA for punch throw test variables (mean and peak speed) Pearson's correlation coefficient for relationships between variables
Effect sizes (Cohen's D) between condition for punch throw tests
Confidence intervals on means for each conditioning for punch throw tests
P3 - Research with Human Participants
Q1. Does the research involve human participants?: Yes
Q2. Will any of the participants be vulnerable?: No
Q3. Is this a clinical trial?: No
If yes, will the placebo group receive a treatment plan after the study? If N/A tick no.: No
Q4. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?: No
Q5. Will tissue samples (including blood) be obtained from participants?: No
Q6. Is pain or more than mild discomfort likely to result from the study?: No
Q7. Will the study involve prolonged testing (activities likely to increase the risk of repetitive strain injury)?: No
Q8. Is there any reasonable and foreseeable risk of physical or emotional harm to any of the participants?: No
Q9. Will anyone be taking part without giving their informed consent?: No
Q10. Is it covert research?: No
Q11. Will the research output allow identification of any individual who has not given their express consent to be identified?: No
Q12. Where data is collected from human participants, outline the nature of the data, details of anonymisation, storage and disposal procedures if these are required (300 - 750): Data collected will include:
1) Name, DOB, Medical history 2) Stature, Body mass
3) Body composition
4) Jump heights
5) Barbell velocity
The participant will provide consent for all relevant information to be published.

Medical data and informed consent will be stored for 5 years by the principal investigator before electronic copies are deleted. This data will be stored online in a SHU managed folder (Q drive). Paper copies will be archived, stored securely in a locked safe and shredded after 5 years.

P4 - Research in Organisations

Q1. Will the research involve working with an external organisation or using data/material from an external organisation?: No

Q2. Do you have granted access to conduct the research?: Yes

P5 - Research with Products and Artefacts

Q1. Will the research involve working with copyrighted documents, films, broadcasts, photographs, artworks, designs, products, programmes, databases, networks, processes, existing datasets or secure data?: No

Q2. Are the materials you intend to use in the public domain?: No

P6 - Human Participants - Extended

Q1. Describe the arrangements for recruiting, selecting/sampling and briefing potential participants.:

Participants will be recruited from a local boxing club using stratified sampling.

Inclusion criteria

Age > 18 years

Must have 1 years experience of boxing training and 1 competitive amateur bout Must have 1 years experience of strength training

Exclusion criteria

No injury in the last 8 weeks

No medication

No visit to the doctor in last 8 weeks for a condition that influences health or ability to perform exercise

Any medical issue highlighted in the pre-screening medical questionnaire deemed to impact on health during assessments

Sample size = 12 - based on professional experience of local boxers able to meet inclusion criteria above. **Q2. Indicate the activities participants will be involved in.:** NA

Q3. What is the potential for participants to benefit from participation in the research?: Participants will understand their punch specific velocity profile which can be used as a basis to improve their strength. **Q4. Describe any possible negative consequences of participation in the research along with the ways in which these consequences will be limited:** Possible injury - this is controlled within the risk assessment.

Q5. Describe the arrangements for obtaining participants' consent.: Participants will read the participant information sheet, have the opportunity to ask questions and finally sign an informed consent form.

Q6. Describe how participants will be made aware of their right to withdraw from the research.: This will be documented on the participant information sheet and explained verbally.

Q7. If your project requires that you work with vulnerable participants describe how you will implement safeguarding procedures during data collection: NA

Q8. If Disclosure and Barring Service (DBS) checks are required, please supply details: NA **Q9. Describe the arrangements for debriefing the participants.:** After the final testing session participants will be able to ask any questions regarding their test results.

Q10. Describe the arrangements for ensuring participant confidentiality. This should include details of: Participants will be provided with a participant number and names will be anonymised. Only the research team will have access to the anonymised data.
Q11. Are there any conflicts of interest in you undertaking this research?: No
Q12. What are the expected outcomes, impacts and benefits of the research?: The validation of a punch specific test is the expected outcome. It will have an impact on the ability of strength and conditioning coaches to profile their athletes strength in a sport specific manner. This will benefit the training boxers.

Q13. Please give details of any plans for dissemination of the results of the research.: The results will be presented an international conference in sport science and published in a sport science journal.
P7 - Health and Safety Risk Assessment
Q1. Will the proposed data collection take place only on campus?
: Yes
Q2. Are there any potential risks to your health and wellbeing associated with either (a) the venue where the research will take place and/or (b) the research topic itself?: None that I am aware of
Q3. Will there be any potential health and safety risks for participants (e.g. lab studies)? If so a Health and Safety Risk Assessment should be uploaded to P8.: Yes
Q4. Where else will the data collection take place? (Tick as many venues as apply)Researcher's Residence: false
Participant's Residence: false
Education Establishment: false
Other e.g. business/voluntary organisation, public venue: false
Outside UK: false
Q8. How will you ensure your own personal safety whilst at the research venue, (including on campus where there may be hazards relating to your study)?: The research team will adhere to University policies and risk assessments for the specific activities
P8 - Attachments
Are you uploading any recruitment materials (e.g. posters, letters, etc.)?: Non Applicable
Are you uploading a participant information sheet?: Yes
Are you uploading a participant consent form?: Yes
Are you uploading details of measures to be used (e.g. questionnaires, etc.)?: Non Applicable **Are you uploading an outline interview schedule/focus group schedule?:** Non Applicable
Are you uploading debriefing materials?: Non Applicable
Are you uploading a Risk Assessment Form?: Yes
Are you uploading a Serious Adverse Events Assessment (required for Clinical Trials and Interventions)?: Non Applicable
Are you uploading a Data Management Plan?: Yes

Upload:

Risk Assessment Body Composition.docx
Risk Assessment Jump Tests.docx
Risk Assessment Landmine Punch.docx
Validation of Landmine Punch Profile_Participant Consent Form.docx
Validation of Landmine Punch Profile Participant Information Sheet.docx

P9 - Adherence to SHU Policy and Procedures
Primary Researcher / PI Sign-off:
I can confirm that I have read the Sheffield Hallam University Research Ethics Policy and Procedures: true
I can confirm that I agree to abide by its principles and that I have no personal or commercial conflicts of interest relating to this project.: true

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Date of PI Sign-off: 12/11/2019
Upload:
P10 - Review
Comments collated by Lead Reviewer (Or FREC if escalated): An interesting piece of work that possesses obvious practical application and benefit to research teams and practitioners. The application is succinct but sufficiently detailed to understand the methodological approach and ethical implications of the study. I'm happy that the submitted paperwork, along with the application, is detailed and robust and that the participants will not be at risk.
I have 1-2 comments that might be note. Firstly, the application doesn't indicate explicitly that the InBody 720 will be used to assess body composition (I am assuming that it is), however this becomes implicit
when reviewing the risk assessment. If participants need to be in a state of undress to gain reliable InBody data, does this pose a risk (again, this might be moot and unimportant if participants remain dressed)?
Also, a sample size of 12 participants; will this sample achieve sufficient statistical power if you're using frequentist inferential statistics (granted you're using a repeated measures design however this might be a methodological consideration for the team more broadly).
Final Decision to be completed by Lead Reviewer (or FREC if escalated): Approved
Date of Final Decision: 25/11/2019
P12 - Post Approval Amendments Amendment 1
In my judgement amendment 1 should be: Select Amendment Outcome **Amendment 2**
In my judgement amendment 2 should be: Select Amendment Outcome **Amendment 3**
In my judgement amendment 3 should be: Select Amendment Outcome

Appendix 4: Conference abstract: Can commercially punch trackers actually recognize different punch types correctly?

CAN COMMERCIAL PUNCH TRACKERS ACTUALLY RECOGNIZE DIFFERENT PUNCH TYPES CORRECTLY?

Dan Omcirk[1] • Tomas Vetrovsky[1] • Jan Padecky[1] • Sophie Vanbelle[2] • Jan Malecek[1] • James J Tufano[1]

[1]Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic

[2]Department of Methodology and Statistics, Maastricht University, Netherlands

PURPOSE

Punch trackers (PT) are marketed to both trained and untrained fighters. However, PTs likely have different algorithms to identify punch type, which may not correctly identify punches thrown by people with different technical levels. This study compared 3 commercially available PTs to determine how well they could recognize specific types of punches thrown by trained fighters (TF) and untrained fighters (UF) while shadow boxing.

METHODS

10 TF (28.1 ± 5.5 y, 83.0 ± 10.9 kg, 178.2 ± 9.2 cm) and 11 UF (27.3 ± 6.1 y, 84.5 ± 12.6 kg, 182.6 ± 7.4 cm) performed 3 rounds of shadow boxing that included a standard set of 54 punches including crosses, jabs, hooks and uppercuts with 10-ounce boxing gloves and 2.5 m boxing wraps holding the PTs in place according to the manufacture's guidelines (Corner - CPT, Everlast - EPT, and Hykso - HPT). The internal algorithms of each PT then determine the type of punch thrown and the total number of each punch type is provided. These values were compared to video recordings where the researcher identified punch type (gold-standard). Due to technical failures, data from 20 subjects was analyzed for CPT, 18 for EPT, and 21 for HPT. Mean absolute percentage errors (MAPE) and mean percentage errors (MPE) were calculated for the total number of punches, and linear mixed effects models were used to explore the effect of technical level (UF vs TF) and punch type on the percentage error. Finally, the sensitivity for individual punch detection was calculated for CPT and HPT (EPT does not provide data for individual punches).

CONTACT

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RESULTS

The punches assessed by PT and video are shown in Table 1. The MAPE for CPT was 0.03 (95% confidence interval, 0.0 to 0.21), for HPT was 0.095 (0.0 to 0.34), and for EPT was 0.13 (0.0 to 0.41). The MPE for CPT was 0.005 (-0.08 to 0.09), for HPT was -0.08 (-0.15 to -0.01), and for EPT was -0.06 (-0.16 to 0.04). The sensitivity for detecting individual punches was 0.74 for CPT (ranging from 0.54 to 0.91 for different punch types) and 0.69 for HPT (range 0.50 to 0.96). When considering all three PTs, the percentage error was significantly lower in TF compared to UF ($p = 0.007$) and was lower for straight punches compared to hooks and uppercuts ($p < 0.001$).

	HPT		EPT		CPT	
	Tracker	Real	Tracker	Real	Tracker	Real
Total TF	53.2 ± 2.8	53.9 ± 0.3	57.3 ± 8.5	54.0 ± 0.0	55.6 ± 4.8	53.9 ± 0.3
Total UF	46.5 ± 7.4	54.0 ± 0.0	45.8 ± 7.0	54.0 ± 0.3	52.7 ± 2.2	53.8 ± 0.6
Jab TF	12.5 ± 2.0	9.2 ± 0.6	11.7 ± 5.1	9.3 ± 0.7	11.1 ± 2.8	9.1 ± 0.3
Jab UF	10.6 ± 2.1	8.8 ± 0.7	12.5 ± 4.9	8.9 ± 0.5	12.0 ± 4.1	8.9 ± 0.3
Cross TF	13.5 ± 4.5	8.8 ± 0.6	10.4 ± 2.5	8.7 ± 0.7	13.3 ± 4.1	8.9 ± 0.3
Cross UF	10.5 ± 1.9	9.1 ± 0.3	9.6 ± 1.8	9.2 ± 0.6	11.7 ± 2.9	9.1 ± 0.3
Left Hook TF	9.1 ± 2.5	9.4 ± 0.7	8.0 ± 2.7	9.3 ± 0.5	8.6 ± 3.4	8.8 ± 0.6
Left Hook UF	4.9 ± 2.1	9.1 ± 0.3	4.2 ± 3.9	9.6 ± 1.2	7.0 ± 3.7	9.3 ± 1.2
Right Hook TF	6.4 ± 1.7	8.8 ± 0.4	8.3 ± 7.7	8.9 ± 0.4	5.3 ± 3.4	9.1 ± 0.8
Right Hook UF	5.9 ± 2.7	9.4 ± 0.8	8.6 ± 3.1	8.9 ± 0.8	4.4 ± 2.5	9.0 ± 0.4
Left Uppercut TF	4.7 ± 2.1	8.0 ± 0.6	6.7 ± 3.3	7.7 ± 0.5	7.0 ± 1.7	7.9 ± 0.5
Left Uppercut UF	6.0 ± 2.9	8.3 ± 0.8	5.9 ± 3.5	8.5 ± 1.2	6.9 ± 2.8	8.2 ± 0.7
Right Uppercut TF	7.0 ± 3.6	9.7 ± 0.6	9.7 ± 5.0	10.1 ± 0.4	9.3 ± 4.0	10.2 ± 0.8
Right Uppercut UF	8.6 ± 1.2	9.4 ± 0.6	5.2 ± 3.8	9.1 ± 1.5	9.9 ± 2.6	9.4 ± 1.2

Table 1. Mean and standard deviation of shadow boxing punches that were recorded by each trackers (Hykso [HPT], Everlast [EPT], and Corner [CPT]) and the real number of punches thrown for trained fighters (TF) and untrained fighters (UF).

CONCLUSION

Of the PTs tested, CPT was the best at identifying the total number of punches per session, in that it neither largely missed punches nor falsely identified a punch that did not occur. When analyzing individual punches (HPT and CPT), HPT missed more punches than CPT, especially uppercuts and hooks. It seems as if being a TF with a better punch technique increases the likelihood that the punch type will be identified correctly.

PRACTICAL APPLICATIONS

HPT and CPT may be used to detect direct punches, and the punch recognition will likely increase as punch technique improves. However, the PTs used in this study likely cannot accurately track punches for untrained punchers, whom most PTs are marketed for.

Appendix 5: Conference abstract: Validation of velocity measurements from different commercial punch trackers and their relationship to punch force

VALIDATION OF VELOCITY MEASUREMENTS FROM DIFFERENT COMMERCIAL PUNCH TRACKERS AND THEIR RELATIONSHIP TO PUNCH FORCE

Dan Omcirk[1] • Tomas Vetrovsky[1] • Jan Padecky[1] • Sophie Vanbelle[2] • Jan Malecek[1] • James J Tufano[1]
[1]Faculty of Physical Education and Sport, Charles University, Prague, Czech Republic
[2]Department of Methodology and Statistics, Maastricht University, Netherlands

PURPOSE

Commercially available punch trackers claim to measure punch speed, force, power, and other arbitrary variables such as intensity scores. However, those claims have not been validated against gold-standard laboratory equipment, and the devices do not specify whether they assess mean or peak values. The purpose of this study was to validate velocity measures of commercially available punch trackers and determine their relationship with actual punch force.

METHODS

20 healthy males (27.8 ± 5.9 y, 83.2 ± 11.8 kg, 180.1 ± 8.5 cm) performed a single testing session that included familiarization, warm-up, and 6 individual (3x estimated 50% of maximal effort and 3x with maximal effort) right cross, right hook, and right uppercut punches in randomized order with 2 minutes rest between each punch type. Each punch was performed with 10-ounce boxing gloves and standard 2.5m boxing wraps that were used to attach the PTs to the wrist according to the manufacturer's guidelines. The Qualisys tracking manager measured peak velocity (QPV) and mean velocity (QMV) and an adjustable wall-mounted force plate (Loadstar sensors) measured peak punch force (FP). For data analysis, all 20 subjects were included for Corner's (CPT) velocity and power measures and Hykso's (HPT) velocity measure, but due to periodical device failure, only 12 subjects were included for StrikeTec's (SPT) velocity measure. The Pearson's correlation coefficient, mean absolute percentage errors (MAPE), and mean percentage errors (MPE) were calculated separately for each PT. Ideally, high correlation coefficients coupled with low MAPE and MPE scores are desired.

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RESULTS

The correlations between PT variables and the gold standard QPV, QMV, and FP are shown in Table 1. HPT velocity displayed a MAPE of 0.21 and an MPE of -0.06 compared to QPV, and a MAPE of 0.64 and an MPE of 0.63 compared to QMV. SPT velocity displayed a MAPE of 0.46 and an MPE of 0.43 compared to QPV and a MAPE of 1.49, and an MPE of 1.49 compared to QMV. CPT power displayed a MAPE of 0.27 and an MPE of -0.09 compared to QPV, and a MAPE of 0.65 and an MPE of 0.58 compared to QMV.

	HPT	SPT	CPT	
	Velocity	Velocity	Power	Velocity
QPV	r = 0.61 (0.54 to 0.68)	r = 0.55 (0.44 to 0.64)	r = 0.58 (0.51 to 0.65)	r = 0.03 (-0.08 to 0.13)
QMV	r = 0.68 (0.62 to 0.74)	r = 0.56 (0.45 to 0.65)	r = 0.59 (0.51 to 0.65)	r = -0.05 (-0.16 to 0.05)
FP	r = 0.23 (0.13 to 0.33)	r = 0.36 (0.23 to 0.48)	r = 0.28 (0.17 to 0.37)	r = 0.43 (0.34 to 0.52)

Table 1. Correlations (Pearson's r) and 95% confidence intervals for three different punch trackers (Hykso [HPT], StrikeTec [SPT], and Corner [CPT]) and their non-defined velocity or power measures compared to gold-standard peak velocity (QPV), mean velocity (QMV), and impact force (FP) measures.

CONCLUSION

None of the PT variables were highly correlated with gold standard velocity or force measures, and users should be aware that their PTs likely do not portray actual movement velocity. Furthermore, CPT users should know that their "power" variable likely refers to actual movement velocity, whereas their velocity variable may refer to something else that may be more representative of punch force.

PRACTICAL APPLICATIONS

The MAPE and MPE values indicate that SPT should not be used if aiming to monitor mean velocity. On the other hand, of the PTs tested here, HPT and CPT may be used to monitor peak velocity if the user is willing to accept the errors that occur within. However, this study only examined the validity of these PT variables, and the reliability was not tested.

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Appendix 6: Conference abstract: The load-velocity profiles of different landmine punch throw variations

INTRA-SESSION RELIABILITY OF DIFFERENT LANDMINE PUNCH THROW VARIATIONS FOR BALLISTIC UPPER BODY TESTING

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PURPOSE

Not only is the landmine punch throw commonly used as an exercise during resistance training, but it is also often used to assess ballistic upper body strength or power. However, the reliability of this exercise has not yet been examined, meaning its use as a test to monitor performance is not yet supported. The purpose of this study was to determine the reliability of the three different landmine punch throw variations, each with three different loads (a barbell with no additional load, +2.5 kg, and +5.0 kg), all performed with the dominant and non-dominant hand.

METHODS

14 healthy boxers (24.1 ± 4.3 y, 72.6 ± 10.1 kg, 176.9 ± 8.3 cm) participated in this study. Each subject participated in a single testing session, which included familiarization, a dynamic warm-up, and landmine punch throw testing. All of the three different landmine punch throw variations (seated without trunk rotation [LPwo], seated with trunk rotation [LPw], and standing with trunk rotation and the use of the legs [LP]; [Figure 1]) were performed with three different loads (olympic barbell, olympic barbell +2.5 kg, and olympic barbell +5kg), all with the dominant hand (DH) and nondominant hand (NH) in a quasi-randomized order. Three trials for each variation-load-hand combination were performed with maximal effort, and peak concentric velocity (via GymAware linear position transducer) was assessed. The intra-session reliability of each variation-load-hand combination was determined along with the intraclass correlation coefficients with their 95 % confidential intervals.

RESULTS

Most variations were highly reliable, with only a few demonstrating only moderate reliability (Table 1). In general, the variations performed with the NH were as reliable, or more reliable, than with the DH (Table 1).

CONCLUSION

All of the landmine punch throw loads and variations were reliable for both hands, allowing the landmine punch throw to be reliably used for upper body ballistic strength and power testing. However, although the NH seemed to result in more reliable data than the DH, future research should confirm whether this holds true for boxers of different calibers, training experiences, weight categories, and the like.

Figure 1. The three different landmine punch throw variations ([A]standing with trunk rotation and the use of the legs, [B] seated with trunk rotation, and [C] seated without trunk rotation).

PRACTICAL APPLICATIONS

Considering the previous lack of choices for reliable sport-specific upper body ballistic testing, the landmine punch throw seems to fill that need. Therefore, the drawbacks of other upper body ballistic tests (e.g., medicine ball chest throw technique, the need for a Smith machine for bench press throws, etc.) are addressed with this linear, simple test that only requires a barbell and a multi-directional landmine attachment.

CONDITION	DOMINANT HAND			NON-DOMINANT HAND		
	ICC	LCI	UCI	ICC	LCI	UCI
LP 20 kg	0.89	0.75	0.96	0.93	0.84	0.97
LP 22.5 kg	0.94	0.85	0.98	0.94	0.84	0.98
LP 25 kg	0.77	0.54	0.91	0.89	0.76	0.96
LPw 20 kg	0.88	0.75	0.96	0.89	0.77	0.96
LPw 22.5 kg	0.82	0.63	0.93	0.95	0.89	0.98
LPw 25 kg	0.93	0.84	0.97	0.92	0.81	0.97
LPwo 20 kg	0.87	0.72	0.95	0.94	0.87	0.98
LPwo 22.5 kg	0.95	0.89	0.98	0.92	0.83	0.97
LPwo 25 kg	0.78	0.55	0.92	0.97	0.94	0.99

Table 1. Intraclass correlation (ICC), with lower (LCI) and upper confidence intervals (UCI) for each landmine punch throw variation (standing with trunk rotation and the use of the legs [LP], seated with trunk rotation [LPw], and seated without trunk rotation [LPwo]) with 20 kg, 22.5 kg, and 25 kg.

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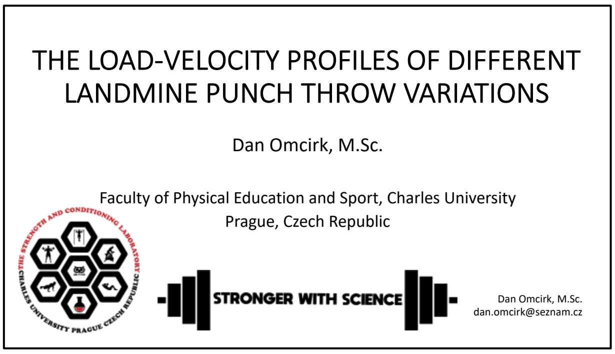
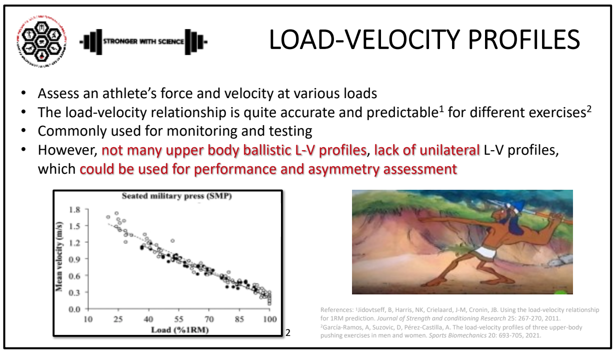
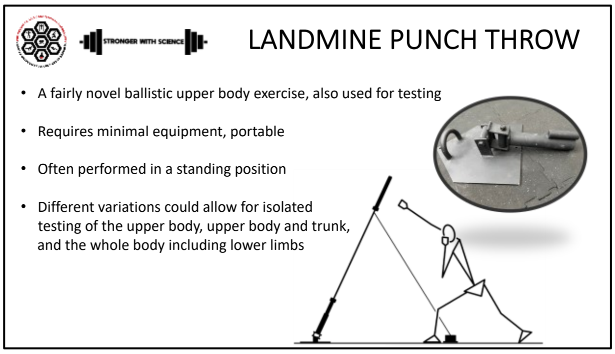
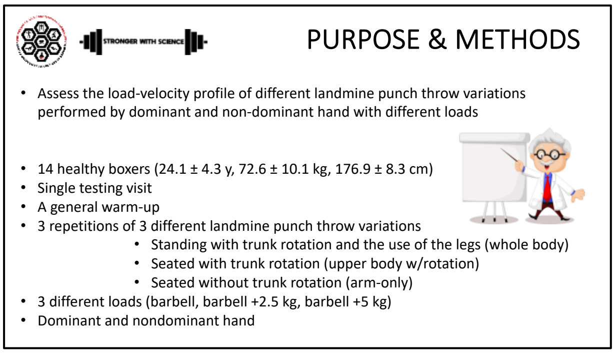
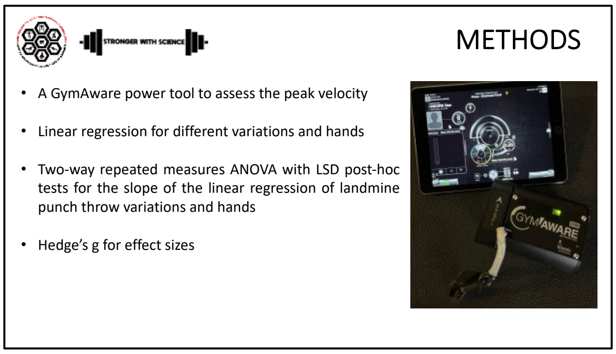
Appendix 7: Conference abstract: Intra-session reliability of different landmine punch throw variations for ballistic upper body testing

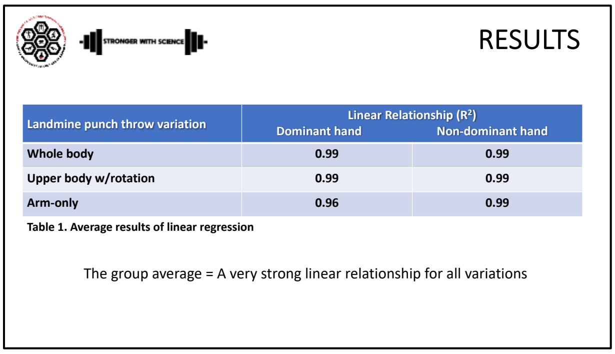




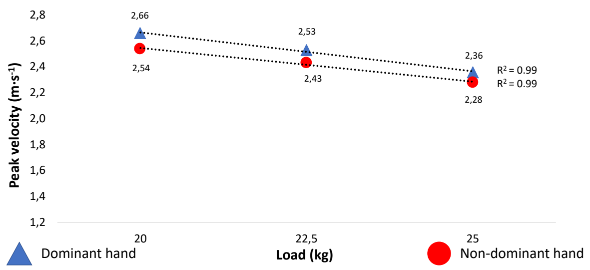




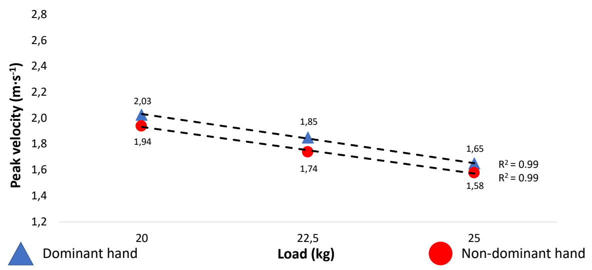




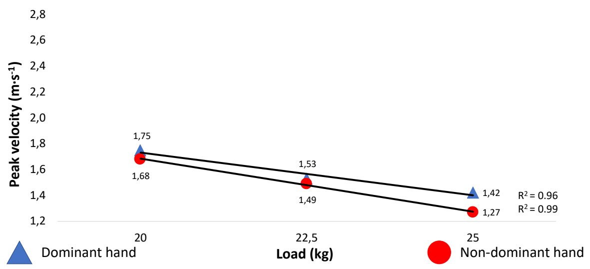
WHOLE BODY

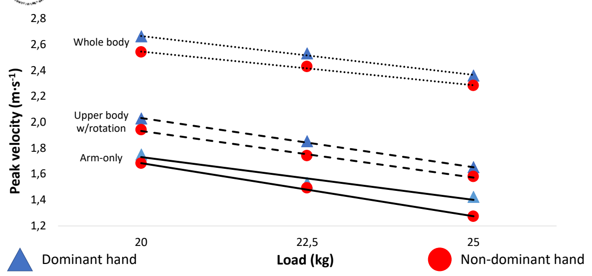


UPPER BODY w/ROTATION

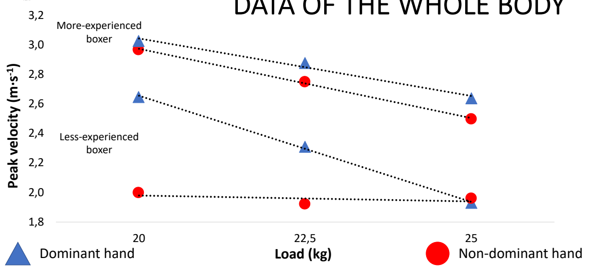


ARM-ONLY





AN EXAMPLE OF INDIVIDUAL DATA OF THE WHOLE BODY



RESULTS

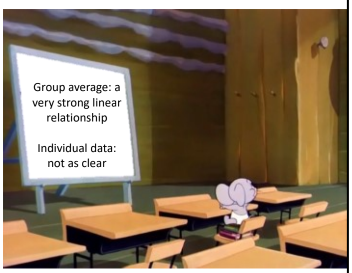
- No significant interactions (p = 0.212)
- No main effects for condition (p = 0.118) or hand (p = 0.539)

Landmine punch throw	Dominant hand	Non-dominant hand	Effect size
Whole body	-0.06 ± 0.05	-0.05 ± 0.04	-0.22
Upper body w/rotation	-0.08 ± 0.04	-0.07 ± 0.02	-0.32
Arm-only	-0.07 ± 0.02	-0.08 ± 0.02	0.50

Table 2. results of the slope of linear regression with their standard deviation

CONCLUSION

- Similar slope of group average regression lines for each variation and hand



PRACTICAL APPLICATION

The landmine punch throw can be used to create an upper-body unilateral load-velocity profile for the following variations:

- Standing with trunk rotation and the use of the legs
- Seated with trunk rotation
- Seated without trunk rotation

Load-velocity profile ⟹ Individually for each athlete

Limitation of this study: Only 2.5 kg difference between each load

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- Cian O'Dea, B.Sc.[2]
- Alan Ruddock, Ph.D.[3,4]
- Daniel Wilson, M.Sc.[4]

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Appendix 8. Raw data presented at study 1: Punch trackers: Correct recognition depends on punch type and training experience

1 AMATEUR				2 AMATEUR		3 AMATEUR				4 FIGHTER				5 AMATEUR				6 AMATEUR			
HYKSO		CORNER		HYKSO		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER	
REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC
J	J	J	J	J	J	C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J
C	C	C	C	C	C	J	J	J	J	C	C	C	0	C	C	C	C	C	C	C	C
RH	0	RH	RH	RH	0	LH	LH	LH	C	RH	RH	RH	RH	RH	RUC	RH	RH	RH	RH	RH	RUC
LH	0	LH	LH	LH	LH	RH	0	RH	J	LH	LH	LH	LH	LH	0	LH	LH	LH	LH	LH	LUC
LUC	0	LUC	LH	LUC	LUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RUC	RH	RUC	RUC	RUC	RUC	LUC	LUC	RUC	RUC	0	J	RUC	RUC	RUC	RH	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	C	J	J	C	C	C	C	RUC	RUC	J	C	J	J	J	J	J	LH	J	J
C	C	C	J	C	C	J	J	J	J	J	J	C	J	C	C	C	C	C	C	C	C
C	C	C	C	C	C	RH	RUC	J	J	C	C	C	C	C	C	C	C	C	C	C	C
LH	J	LH	J	LH	LH	LH	0	LH	LH	C	C	LH	LH	LH	0	LH	LH	LH	LH	LH	J
RH	RH	RH	RH	RH	C	LH	LUC	LH	LH	LH	LH	RH	RH	RH	RH	RH	RUC	RH	RH	RH	RUC
LUC	0	LUC	LH	LUC	LH	RUC	C	RUC	RUC	RH	RH	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	LUC
RUC	RH	RUC	RUC	RUC	RUC	LUC	RUC	LUC	LUC	LUC	LH	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	J	J	J	C	RUC	J	J	RUC	RUC	J	LH	J	J	J	0	J	J	J	J
LUC	0	LUC	LH	LUC	LUC	RUC	RUC	LH	C	J	J	LUC	RH	LUC	LUC	LUC	LUC	LUC	LUC	LUC	RUC
RH	C	RH	RH	RH	RH	RH	0	RUC	RUC	LUC	LUC	RH	LUC	RH	RUC	RH	RUC	RH	RH	RH	LUC
LH	0	LH	LH	LH	LUC	RUC	C	RH	J	RH	RUC	LH	RUC	LH	LH	LH	LH	LH	LH	LH	LH
RUC	RH	RUC	RUC	RUC	C	LH	J	LUC	LUC	LH	LH	RUC	LH	RUC	RUC	RUC	0	RUC	RUC	RUC	RUC
J	J	J	J	J	J	C	J	C	J	RUC	RH	J	LH	J	J	J	J	J	J	J	J
C	C	C	C	C	C	J	C	J	C	J	J	C	J	C	C	C	C	C	C	C	LH
LH	LUC	LH	LH	LH	J	RH	J	LH	C	C	C	LH	C	LH	0	LH	LH	LH	LH	LH	C
C	C	C	C	C	C	J	0	J	J	LH	LH	C	C	C	C	C	C	C	C	C	J
J	J	J	J	J	J	C	LUC	C	C	C	C	J	J	J	0	J	J	J	J	J	C
RH	RUC	RH	RUC	RUC	RUC	RH	0	RH	J	J	J	RUC	RH	RUC	RUC	RUC	0	RUC	RH	RUC	RUC
LUC	0	LUC	LH	LUC	LUC	RUC	0	RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RH	RH	RH	RH	RH	C	LH	LH	LH	C	LUC	LUC	RH	RH	RH	RUC	RH	0	RH	RH	RH	RH
J	J	J	J	J	J	LUC	0	C	C	RH	RUC	J	LH	J	J	J	J	J	J	J	0
RH	RUC	RH	RH	RH	RH	LH	0	LH	LH	J	J	RH	RH	RH	0	RH	RH	RH	RH	RH	RH
LH	J	LH	LH	LH	LH	RH	0	RH	RH	RH	RUC	LH	LH	LH	J	LH	J	LH	LH	LH	J
RH	C	RH	RH	RH	C	LH	J	LH	LUC	LH	LH	RH	RH	RH	RH	RH	0	RH	C	RH	LH
LH	LH	LH	LH	LH	LUC	RH	LUC	RH	LUC	RH	RH	LH	LH	LH	0	LH	LH	LH	J	LH	LH
RUC	RUC	RUC	RUC	RUC	RUC	LUC	RUC	LUC	J	LH	LH	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LUC	0	LUC	LH	LUC	LUC	RH	J	RUC	RUC	RUC	RH	LUC	LUC	LUC	LH	LUC	LUC	LUC	LUC	LUC	LUC
RUC	RUC	RUC	RUC	RUC	RH	LUC	0	LH	LH	LUC	J	RUC	RUC	RUC	RUC	RUC	0	RUC	RUC	RUC	RUC
LUC	0	LUC	LUC	LUC	LUC	RUC	C	RH	J	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	LUC
C	C	C	C	C	C	J	0	J	J	LUC	LUC	C	C	C	C	C	C	0	J	C	C
LH	J	LH	LH	LH	LUC	RH	LUC	RH	J	C	C	LH	LH	LH	LH	LH	LH	C	C	LH	C
C	C	C	C	C	C	C	RUC	C	C	LH	LH	C	C	C	C	C	C	LH	LH	C	LH
RUC	RUC	RUC	RUC	RUC	RUC	LUC	0	LUC	LUC	C	C	RUC	RUC	RUC	RUC	RUC	RUC	C	C	RUC	RUC
LUC	LUC	LUC	LH	LUC	LUC	RUC	J	RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	RUC	RUC	LUC	LH
J	J	J	J	J	J	C	0	C	C	LUC	LH	J	J	J	J	J	J	LUC	LUC	J	J
RH	RUC	RH	RUC	RH	C	LH	0	LH	LH	J	J	RH	RH	RH	RH	RH	RH	J	J	RH	RH
RUC	RUC	RUC	RUC	RUC	RUC	LUC	0	LUC	LUC	RH	RH	RUC	RUC	RUC	0	RUC	RUC	RH	RH	RUC	LH
LH	LH	LH	LH	LH	J	RH	RH	RH	RH	RUC	RUC	LH	LH	LH	LH	LH	LH	RUC	RUC	LH	RUC
RH	RH	RH	RH	RH	RH	LUC	0	0	0	LH	LH	RH	RH	RH	RUC	RH	RH	LH	LUC	RH	RH
RUC	RUC	RUC	RUC	RUC	C	LH	0	0	0	0	J	RUC	RUC	RUC	RH	RUC	RUC	RH	RH	RUC	RUC
C	C	C	J	C	C	J	J	J	J	RH	RUC	C	C	C	C	C	C	RUC	RUC	C	C
J	J	J	C	J	J	C	C	C	C	RUC	RUC	J	J	J	J	J	J	C	C	J	J
C	C	C	C	C	C	J	J	J	J	C	C	C	C	J	J	C	C	J	J	C	C
LUC	LUC	LUC	LUC	LUC	LUC	RUC	RUC	LH	C	J	J	LUC	LUC	LUC	LUC	LUC	LUC	C	C	LUC	LH
LH	0	LH	LH	LH	LH	RH	0	LH	C	C	C	LH	LH	LH	0	LH	LH	LUC	LUC	LH	LH
J	J	J	J	J	J	C	0	C	C	LUC	LUC	J	J	C	C	J	0	LH	LH	C	C
RUC	RUC	RUC	RUC	RUC	RUC	LUC	J	LUC	LUC	LH	LUC	RUC	RUC	RUC	0	RUC	RUC	J	J	RUC	RUC
RH	RH	RH	RH	RH	RH	LH	LH	LH	C	J	J	RH	RH	RH	RUC	RH	RUC	RUC	RUC	RH	RH
										0	J							RH	RH		
										RH	RUC										
										0	J										
										RUC	RUC										

7 AMATEUR				8 FIGHTER				9 FIGHTER				10 AMATEUR				11 AMATEUR			
HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER	
REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC
C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
LH	LH	LH	LH	RH	C	RH	RH	RH	RH	RH	C	RH	0	RH	RH	RH	RH	RH	C
RH	J	RH	RH	LH	J	LH	J	LH	LH	LH	LH	LH	0	LH	LH	LH	LH	LH	J
RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	LUC	LUC	0	LUR	LUC	LUC	LUC	LUC	LUC
LUC	LH	LUC	LUC	RUC	RH	RUC	RUC	RUC	C	RUC	C	RUC	0	RUC	RUC	RUC	RUC	RUC	RUC
C	C	C	J	J	J	J	J	J	J	J	J	J	0	J	J	J	J	J	J
J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RH	J	RH	RUC	LH	LUC	LH	J	LH	LH	LH	LH	LH	0	LH	LH	LH	J	LH	J
LH	C	LH	RUC	RH	C	RH	RH	RH	C	RH	C	RH	0	RH	RH	RH	RUC	RH	C
RUC	RUC	RUC	LH	LUC	LUC	LUC	LUC	LUC	LH	LUC	LH	LUC	0	LUC	LH	LUC	LUC	LUC	LH
LUC	LUC	LUC	LUC	RUC	RUC	RUC	RUC	RUC	C	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
J	J	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	LUC	LUC	0	LUC	LUC	LUC	LUC	LUC	LUC
LH	LUC	LH	LH	RH	C	RH	RH	RH	C	RH	RH	RH	RH	RH	RH	RH	RH	RH	RUC
RH	RH	RH	RH	LH	J	LH	J	LH	J	LH	LH	LH	LH	LH	LH	LH	LUC	LH	LH
LUC	LUC	LUC	LUC	RUC	RH	RUC	RUC	RUC	RH	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RH	RH	RH	RUC	LH	J	LH	LH	LH	J	LH	LH	LH	0	LH	LH	LH	LUC	LH	LH
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
LUC	LH	LUC	LUC	RUC	RUC	RUC	RUC	RUC	C	RUC	RH	RH	RH	RUC	RUC	RUC	RUC	RUC	RUC
RUC	RUC	RUC	RUC	LUC	0	LUC	LUC	LH	J	LUC	LUC	LUC	0	LUC	LH	LUC	LUC	LUC	LUC
LH	LH	LH	LUC	RH	C	RH	C	RUC	C	RH	RH	RH	0	RH	RH	RH	RH	RH	C
C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
LH	LH	LH	LH	RH	RH	RUC	RUC	RH	RH	RH	C	RH	RH	RH	RH	RH	RH	RH	RH
RUC	RUC	RH	LH	LH	J	LUC	LUC	LH	LH	LH	LH	LH	0	LH	LH	LH	LH	LH	LH
LH	C	LH	RUC	RH	C	RUC	RUC	RH	C	RH	C	RH	0	RH	RH	RH	RH	RH	RH
RH	RH	RH	RH	LH	0	LH	J	LH	LH	LH	J	LH	0	LH	LH	LH	LH	LH	LH
LUC	LUC	LUC	LUC	RUC	RH	RUC	RUC	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	0	LUC	LUC	LUC	LUC	LUC	LUC
LUC	LUC	LUC	LH	RUC	RUC	RUC	RUC	RUC	C	RUC	C	RUC	RUC	RUC	RUC	RUC	RH	RUC	LUC
RUC	RUC	RUC	RUC	LUC	0	LUC	LUC	LUC	LH	LUC	LUC	LUC	0	LUC	LUC	LUC	LUC	LUC	RUC
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RH	RH	RH	RH	LH	LH	LH	J	LH	LH	LH	J	LH	LH	LH	LH	LH	LH	LH	C
C	C	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	LUC
LUC	LUC	LUC	LUC	RUC	RUC	RUC	RUC	RUC	C	RH	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
RUC	RUC	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LH	RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
C	C	C	C	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
LH	C	LH	C	RH	C	RH	C	RH	C	RH	RH	RH	C	RH	RH	RH	RH	RH	C
LUC	LH	LUC	LH	RUC	RUC	RUC	RUC	RUC	0	RUC	C	RUC	RUC	RUC	RUC	RUC	RH	RUC	RUC
RH	RUC	RH	RUC	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH	J	LH	LH	LH	LH
LH	C	LH	LH	RH	RH	RH	RH	RH	C	RH	RH	RH	RH	RH	RH	RH	RH	RH	RH
LUC	LUC	LUC	LUC	RUC	RUC	RUC	RUC	RUC	RH	RUC	C	RUC	0	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	J	C	C	J	J	C	C	C	C	C	C	C	C	C	C	C	C
C	C	C	C	J	J	C	C	J	J	J	J	J	J	J	J	J	J	J	J
J	J	J	J	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RUC	RUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LH	LUC	LUC	LUC	LUC
RH	J	RH	RH	LH	LH	LH	J	LH	LH	LH	LH	LH	LH	LH	LH	LH	LUC	LH	LH
C	C	C	C	J	J	J	J	J	J	J	J	C	C	J	J	J	J	J	J
LUC	LUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LH	LUC	LH	LH	RH	RH	RH	RH	RH	RH	RH	C	RH	RH	RH	RH	RH	RH	RH	C

12 AMATEUR				13 FIGHTER				14 FIGHTER				15 AMATEUR				16 FIGHTER			
HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER	
REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC
J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J	J
C	C	C	C	C	C	C	C	0	J	C	C	C	C	C	C	C	C	C	C
RH	J	RH	C	RH	RH	RH	RH	C	C	RH	RH	RH	0	RH	RH	RH	C	RH	C
LH	0	LH	J	LH	LH	LH	LH	0	J	LH	LH	LH	0	LH	LH	LH	LH	LH	J
LUC	0	LUC	LUC	LUC	LUC	LUC	LUC	RH	RH	0	RUC	LUC	0	LUC	LUC	LUC	LH	LUC	LUC
RUC	0	RUC	RUC	RUC	RUC	RUC	RUC	LH	LUC	LUC	LH	RUC	0	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	J	J	J	J	J	LUC	0	0	RUC	J	0	J	J	J	J	J	C
C	C	C	C	C	C	C	C	0	J	0	J	C	C	C	C	C	C	C	J
C	C	C	C	C	C	J	J	RUC	RUC	RUC	RUC	C	C	C	C	C	C	C	C
LH	LH	LH	J	LH	LH	RH	C	J	J	J	J	LH	LUC	LH	LUC	LH	LH	LH	J
RH	0	RH	C	RH	RH	RH	RH	C	C	C	C	RH	RH	RH	RUC	RH	C	RH	LUC
LUC	LUC	LUC	0	LUC	LUC	LUC	LUC	C	C	C	C	LUC	LH	LUC	LUC	LUC	LH	LUC	C
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LH	LH	LH	LH	RUC	0	RUC	RUC	RUC	RUC	RUC	C
J	J	J	J	J	J	J	J	RH	RH	RH	RH	J	J	J	J	J	J	J	J
LUC	LUC	LUC	LUC	LUC	0	LUC	LUC	LUC	LH	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RH	RH	RH	RH	RH	RH	RH	RH	RUC	RUC	0	J	RH	RH	RH	RUC	RH	C	RH	C
LH	0	LH	LH	LH	LH	LH	LH	J	J	RUC	RUC	LH	LH	LH	LH	LH	LH	LH	RUC
RUC	RUC	RUC	0	RUC	RUC	RUC	RUC	LUC	LUC	J	J	RUC	0	RUC	RUC	RUC	RH	RUC	J
J	J	J	J	J	J	J	J	RH	RUC	LUC	LH	J	J	J	J	J	J	J	J
C	C	C	C	C	C	C	C	LH	LH	0	RH	C	C	C	C	C	C	C	C
LH	J	LH	LH	LH	LH	LH	LH	RUC	RH	RH	RUC	LH	0	LH	LUC	LH	J	LH	J
C	C	C	C	C	C	C	C	J	J	LH	LH	C	C	C	C	C	C	C	C
J	J	J	J	J	J	J	J	C	C	RUC	RUC	J	J	J	J	J	J	J	C
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LH	LH	J	J	RUC	0	RUC	RUC	RUC	RH	RUC	J
LUC	LH	LUC	LUC	LUC	0	LUC	LUC	C	C	C	C	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RH	RH	RH	RH	RH	RH	RH	RH	J	J	LH	J	RH	RUC	RH	RUC	RH	C	RH	C
J	J	J	J	J	J	J	J	RUC	RUC	C	C	J	J	J	J	J	J	J	J
RH	0	RH	RH	RH	RH	RH	RH	LUC	LH	J	J	RH	RH	RH	RH	RH	C	RH	C
LH	J	LH	LH	LH	LH	LH	LH	RH	RH	RUC	C	LH	0	LH	LUC	LH	LH	LH	LH
RH	0	RH	RH	RH	C	RH	RH	J	J	LUC	LH	RH	0	RH	RH	RH	C	RH	C
LH	0	LH	J	LH	LH	LH	LH	RH	RH	RH	RUC	LH	0	LH	LH	LH	LH	LH	J
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LH	LH	J	J	RUC	RUC	RUC	RUC	RUC	RH	RUC	RUC
LUC	0	LUC	LUC	LUC	LUC	LUC	LUC	RH	RH	RH	RH	J	J	LUC	LUC	LUC	LUC	LUC	LUC
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LH	LH	0	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LUC	0	LUC	LUC	LUC	LUC	LUC	LUC	RUC	RH	LH	LH	LUC	0	LUC	LUC	LUC	LUC	LUC	LUC
C	C	C	C	J	J	C	C	LUC	LH	RH	RH	C	C	C	C	C	C	C	C
LH	0	LH	LH	LH	LH	LH	LH	RUC	RUC	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH
C	C	C	C	J	J	C	C	LUC	LUC	0	RUC	C	C	C	C	C	C	C	C
RUC	RUC	RUC	0	RUC	RUC	RUC	RUC	C	C	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LUC
LUC	0	LUC	LUC	LUC	LUC	LUC	LUC	LH	LH	LUC	J	LUC	LH	LUC	LUC	LUC	LUC	LUC	C
J	J	J	J	J	J	J	J	C	C	RUC	RUC	J	J	J	J	J	J	J	J
RH	0	RH	C	RH	RH	RH	RH	RUC	RUC	LUC	LUC	RH	RH	RH	RUC	RH	C	RH	C
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	LUC	LH	C	0	RUC	RUC	RUC	RUC	RUC	RH	RUC	C
LH	LUC	LH	LH	LH	LH	LH	LH	J	J	LH	LH	LH	LUC	LUC	LUC	LH	LH	LH	LH
RH	RH	RH	C	RH	RH	RH	RH	RH	RH	RUC	RUC	RH	RH	RH	RH	RH	C	RH	C
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RH	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	C
C	C	C	C	C	C	C	C	LH	LH	LUC	J	C	C	C	C	C	C	C	J
J	J	J	J	J	J	J	J	RH	RH	0	C	J	J	J	J	J	J	J	C
C	C	C	C	C	C	C	C	0	J	0	C	C	C	C	C	C	C	C	C
LUC	LH	LUC	LUC	LUC	LUC	LUC	LUC	RUC	RUC	J	J	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
LH	0	LH	LH	LH	LH	LH	LH	C	C	RH	RH	LH	LH	LH	LH	LH	LH	LH	J
J	J	J	J	J	J	J	J	J	J	RUC	RUC	J	J	J	J	J	J	J	J
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	C	LH	LH	RUC	RUC	RUC	RUC	RUC	RH	RUC	RUC
RH	RH	RH	RH	RH	RH	RH	RH	LUC	LUC	RH	C	RH	RUC	RH	RH	RH	C	RH	C
								LH	0	0	J								
								J	J	RUC	RUC								
								0	LH	C	C								
								RUC	RUC	J	J								
								0	J	0	LH								
								RH	C	C	RUC								
										0	C								
										LUC	LH								
										LH	LH								
										J	J								
										0	C								
										0	LUC								
										RUC	RUC								
										0	C								
										RH	C								

17 FIGHTER				18 AMATEUR				19 FIGHTER				20 FIGHTER				21 FIGHTER			
HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER		HYKSO		CORNER	
REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC	REAL	REC
J	J	J	J	J	J	J	J	J	J	J	LH	J	J	J	J	J	J	J	J
C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RH	C	RH	C	RH	RH	RH	RH	RH	C	0	J	RH	RH	RH	C	RH	RH	RH	RH
LH	LH	LH	LH	LH	J	LH	J	LH	0	RH	C	LH	LH	LH	LH	LH	J	LH	LH
LUC	LUC	LUC	LUC	LUC	LUC	LUC	J	LUC	LUC	LH	J	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RUC	RH	RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	LUC	LUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	J	J	J	J	J	J	J	RUC	RUC	J	J	J	J	J	J	J	0
C	C	C	C	C	C	C	C	C	C	J	LH	C	C	C	C	C	C	C	C
C	C	C	C	C	C	C	C	C	0	C	C	C	C	C	C	C	C	C	C
LH	J	LH	LH	LH	J	LH	J	LH	LH	C	C	LH	LH	LH	LUC	LH	0	0	0
RH	C	RH	C	RH	RH	RH	RUC	RH	C	LH	LH	RH	RH	RH	C	RH	RH	RH	RH
LUC	LH	LUC	LH	LUC	LH	LUC	J	LUC	LH	RH	RH	LUC	LUC	LUC	LUC	LUC	0	LUC	LUC
RUC	RH	RUC	0	RUC	RUC	RUC	C	RUC	RH	LUC	LUC	RUC	RUC	RUC	RUC	RUC	RUC	RH	RH
J	J	J	J	J	J	J	J	J	J	RUC	RUC	J	J	J	J	J	J	J	J
LUC	J	LUC	LUC	LUC	J	LUC	J	LH	J	J	LH	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RH	C	RH	RH	RH	RH	RH	RUC	RH	C	LUC	LUC	RH	RH	RH	RUC	RH	0	RH	RH
LH	J	LH	LH	LH	LH	LH	J	LH	J	RH	RH	LH	LH	LH	LH	LH	LH	LH	LH
RUC	RUC	RUC	RUC	RUC	C	RUC	C	RUC	RUC	LH	J	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
J	J	J	J	J	J	J	0	J	J	RUC	RUC	J	J	J	C	J	J	J	J
C	C	C	C	C	C	C	C	C	C	J	LH	C	C	C	J	C	C	C	C
LH	LH	LH	LH	LH	J	LH	J	LH	J	C	C	LH	LUC	LH	LH	LH	LH	LH	LH
C	RH	C	C	C	C	C	C	C	RH	LH	J	C	C	C	C	C	C	C	C
J	J	J	RUC	J	J	J	J	J	J	0	J	J	J	J	RUC	J	J	J	J
RUC	0	RUC	J	RH	RH	RUC	C	RUC	C	C	C	RUC	RUC	RUC	J	0	0	RUC	RUC
LUC	J	LUC	C	LUC	J	LUC	J	LUC	LH	J	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
RH	C	RH	LH	RH	RH	RH	RUC	RH	RUC	RUC	RUC	RH	RH	RH	RUC	RH	RH	RH	RH
J	J	J	J	J	J	J	J	J	J	LUC	LUC	J	J	J	J	J	J	J	0
RH	C	RH	C	RH	RH	RH	C	RH	C	RH	RUC	RH	RH	RH	RH	RH	RH	RH	RH
LH	LH	LH	LH	LH	J	LH	LUC	LH	LUC	J	LH	LH	LH	LH	LH	LH	LH	LH	LH
RH	C	RH	C	RH	RUC	RH	RUC	RH	C	RH	RH	RH	RH	RH	C	RH	0	RH	RH
LH	J	LH	J	LH	LH	LH	J	LH	J	LH	LH	LH	LH	LH	LH	LH	LH	LH	LH
RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	RUC	RH	RH	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LUC	LH	LUC	LUC	LUC	LH	LUC	J	LUC	LH	LH	J	LUC	LH	LH	LH	LH	0	LUC	LH
RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	RUC	RH	RUC	C	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LUC	J	LUC	LUC	LUC	LH	LUC	J	LUC	LH	LUC	LH	LUC	LUC	LUC	LUC	LUC	J	LUC	LUC
C	C	C	C	C	RH	C	C	C	C	RUC	C	C	C	C	C	C	C	C	C
LH	LH	LH	LH	LH	LH	LH	J	LH	J	LUC	LH	LH	LH	LH	LH	LH	LH	LH	LH
C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
RUC	RUC	RUC	LUC	RUC	C	RUC	RUC	RUC	RH	LH	J	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LUC	LH	LUC	RUC	LUC	LUC	LUC	J	LUC	LH	C	C	LUC	LH	LUC	LUC	LUC	LH	LUC	LUC
J	J	J	J	J	J	J	J	J	J	RUC	C	J	J	J	J	J	J	J	J
RH	C	RH	C	RH	RH	RH	RH	LH	C	LUC	LUC	RH	RH	RH	C	RH	RH	RH	RH
RUC	RH	RUC	RUC	RUC	RUC	RUC	C	RUC	RH	J	LH	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
LH	J	LH	LH	LH	LUC	LH	LUC	LH	LH	RH	C	LH	LH	LH	LH	LH	LH	LH	LH
RH	C	RH	C	LH	LH	RH	RUC	RH	C	RUC	RUC	RH	RUC	RH	RUC	RH	RH	RH	RH
LUC	LH	RUC	RUC	RUC	RUC	RUC	C	LUC	LH	LH	LH	LUC	LUC	RUC	RUC	RUC	RUC	RUC	RUC
C	C	C	C	C	C	C	C	C	C	RH	RH	C	C	C	C	J	J	J	J
J	J	J	J	J	J	J	J	J	J	0	J	J	J	J	J	C	C	C	C
C	C	C	C	C	C	C	C	C	C	RUC	RUC	C	C	C	C	C	C	C	C
LUC	LUC	LUC	LUC	LUC	LUC	LUC	J	LH	J	0	J	LUC	LUC	LUC	LUC	LUC	LUC	LUC	LUC
LH	LH	LH	LH	RH	RH	LH	J	LUC	LH	C	C	LH	LH	LH	LH	LH	J	LH	LH
J	0	J	J	J	J	J	J	J	J	J	LUC	J	J	J	J	J	J	J	J
RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC	C	0	J	RUC	RUC	RUC	RUC	RUC	RUC	RUC	RUC
RH	C	RH	C	RH	RH	RH	RUC	RH	C	C	C	RH	RH	RH	RH	RH	C	RH	RH
										LUC	LUC								
										LH	J								
										J	LH								
										RUC	C								
										RH	RH								

Appendix 9. The Pearson's correlations and confidence intervals (95%) for the Corner Power G against gold-standard peak velocity for different punch intensities (50% and 100%). Mean percentage error (MPE) and mean absolute percentage error (MAPE) for Corner Power G. For reference, MPE and MAPE values closer to zero are the most desirable

Corner Power G			
Intensity	r	MPE	MAPE
50%	0.45 (0.32 - 0.56)	-5%	31%
100%	0.60 (0.50 - 0.69)	-13%	24%

	Hykso		StrikeTec		Corner			
	Peak Velocity		Speed		Power G		Speed	
	n	ICC	n	ICC	n	ICC	n	ICC
RS 50	20	0.80 (0.63 - 0.91)	10	0.37 (-0.04 - 0.76)	20	0.33 (0.06 - 0.62)	20	0.92 (0.83 - 0.96)
RS 100	20	0.43 (0.16 - 0.69)	8	0.93 (0.78 - 0.98)	19	0.25 (-0.02 - 0.55)	19	0.86 (0.73 - 0.94)
RH 50	19	0.78 (0.60 - 0.90)	11	-0.07 (-0.32 - 0.37)	16	-0.08 (-0.30 - 0.28)	16	0.80 (0.61 - 0.92)
RH 100	15	0.72 (0.48 - 0.88)	11	0.69 (0.37 - 0.90)	17	0.75 (0.53 - 0.89)	17	0.56 (0.27 - 0.79)
RUC 50	20	0.57 (0.31 - 0.78)	9	0.42 (0.05 - 0.79)	18	0.40 (0.10 - 0.68)	18	0.59 (0.32 - 0.80)
RUC 100	18	0.12 (-0.14 - 0.46)	7	0.62 (0.15 - 0.91)	17	0.04 (-0.19 - 0.37)	17	0.66 (0.41 - 0.85)

Appendix 10. The intraclass correlation coefficients of Hykso, StrikeTec, and Corner and their non-defined velocity/speed or power values with their lower and upper confidence intervals

Appendix 11. Confirmation of submission