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The manifestations of fatigue in amateur boxing performance

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ABSTRACT

A subjective method of judgment, the "Ten Point Must-System" (TPMS), was introduced into amateur boxing in 2013. To be successful, boxers must deliver forceful punches and exert dominance over an opponent. There has been limited research examining the strategies used by boxers to win fights under the TPMS and whether these strategies induce fatigue that is sufficient to significantly affect punch force. The overall objective of the five studies contained in this thesis was to describe, in relation to fatigue, the performance characteristics of male amateur boxers under the TPMS, and improve our understanding of the physical characteristics associated with punch force production in highly-trained male amateur boxers.

The first study describes technical and behavioural patterns as well as perceptions of effort and fatigue in winning and losing boxers during competition bouts. Winners were found to punch more accurately than losers (33% vs. 23% of punches were landed and 17% vs. 27% were air punches) but the total number of punches were similar. Clinch time, guard drops, and perceptions of effort and fatigue all increased, and bouncing decreased in all boxers over rounds. Regression analysis revealed that in combination, the percentage of punches landed and movement style correctly classified 85% of bout outcomes. Boxers appear to use tactical strategies throughout bouts to pace their effort and minimise fatigue, but these did not influence bout outcome. Thus, judges use several performance indicators, including punch accuracy (but not number) and movement style to (subjectively) assess dominance and determine a winner.

To understand the interaction between punch force and fatigue-related behaviour, a boxing-specific, laboratory-based test (3-min punch test; 3MPT) was designed to measure punch force (N) and force-time variables (i.e. impulse and various rate of force development variables; RFD). The punch force measurement system had high mechanical reliability and accuracy (CV < 0.1%). Typical error and smallest worthwhile changes comparisons revealed that the 3MPT could detect moderate and large changes in performance, however within-day reliability improved from day 1 - 2 (CVs of 3.1 - 13.8% vs. 2.3 - 5.1%), indicating a possible learning effect. Thus, repeat-trial familiarisation is suggested to reduce between-test variability. Studies 3 - 5 then utilised this system to examine factors that may influence punch force delivery.

In Study 3, correlation and regression analyses revealed significant ($p < 0.05$) relationships between peak punch force and forces measured in countermovement jump and isometric mid-

thigh pull tests (i.e. lower-body strength) as well as body mass, but not RFD, in the lower body. No meaningful relationships between punch performance characteristics and any upper-body strength or power parameters were identified. The results of Study 3 show lower-body strength, but not RFD was significantly and positively related to peak punch force, however upper-body strength and power did not discriminate between boxers who punched with higher or lower peak force. In Study 4, punch force characteristics, were measured in the 3MPT of highly-trained male amateur boxers before (ROW_{pre}) and after (ROW_{post}) 9 × 1-min bouts of rowing. This was designed to induce fatigue in lower limb, trunk, and arm flexion muscles whilst leaving arm extensor muscles (primary punch muscles) non-fatigued. Significant reductions in punch force were found ROW_{post} compared to ROW_{pre} for all punch types, and significant delays in the time to reach specific force levels and relative percentages of peak force (i.e. RFD) occurred in all punches except the jab. Thus, punches that particularly rely on lower-limb force production and trunk rotation (crosses and hooks) were most affected. Speculatively, ground reaction force generation was affected by fatigue, however since the jab relies predominantly on arm extension, punch force was less affected by lower-limb fatigue.

In Study 5, the effect of non-specific muscle fatigue (rowing; ROW; as described in Study 4) on punch force production was also examined using the 3MPT, with additional comparisons between control (CON; 75 min rest) and boxing (BOX; competitive boxing bout [3 × 3 min]) conditions in a population of highly-trained male amateur boxers. Significant punch force reductions from ROW_{pre} to ROW_{post} in lead-hand hooks and jabs were observed, however no significant differences were present in CON or BOX, and RFD variables remained unchanged in all conditions. These results suggest that reductions in punch performance after rowing arise from fatigue in the lower body and trunk muscles, whilst boxing is likely to cause fatigue in other body segments that have less influence on punch force production; it is also speculated that boxers use pacing strategies to maintain punch force during fatiguing boxing bouts.

The general findings of this thesis were: technical and behavioural (possibly altered by fatigue) actions influence judge perception under the TPMS, and success requires high levels of punch accuracy; lower-body (but not upper-body) strength rather than RFD was associated with punch force production; lower-body and trunk fatigue significantly reduced punch force, supporting the theory lower-body strength is important to produce punch force; and, boxers maintained the ability to produce punch force throughout a boxing bout, possibly because fatigue was not accumulated in the lower limb and trunk muscles (partly due to boxers using pacing strategies).

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Chapter 4 (Study 2):

Dunn, E.C., Humberstone, C.E., Iredale, K.F. & Blazevich, A.J. A damaging punch: assessment and application of a method to quantify punch performance, *Translational Sports Medicine*, 2019;00:1–7.

Chapter 5 (Study 3):

Dunn, E.C., Humberstone, C.E., Franchini, E., Iredale, K.F. & Blazevich, A.J. Relationships between punch impact force and upper- and lower-body muscular strength and power in highly-trained amateur boxers. *In review: Journal of Strength and Conditioning Research,* 2019

List of conference presentations and proceedings during candidature:

Dunn, E. C., Martin, D. T., Humberstone, C. E., Maloney, M. A., Blazevich, A.J., & Iredale, K.F. Occurrence of haemoglobinuria in judo athletes during competition. *21st Annual Applied Physiology Conference*, Canberra, Australia, 10-11 November 2014

Dunn, E. C., Martin, D. T., Humberstone, C. E., Maloney, M. A., Blazevich, A.J., & Iredale, K.F. Effects of tournament judo on haemoglobin and protein in the urine: *62th Annual American College of Sports Medicine*. San Diego, USA, 26-30 May, 2015

Dunn, E. C., Humberstone, C. E., Iredale, K. F., Martin, D. T., & Blazevich, A. J. Can you bounce your way to success? A comparison of winner and losing boxers in Australia. *22nd Annual Applied Physiology Conference,* Perth, Australia, 12-13 November 2015

Dunn, E.C., Humberstone, C. E., Irelade, K.F., & Blazevich, A. J. (2016), Changes in behaviour, strategy and effort perception during elite amateur boxing. *Exercise and Sport Science Australia Conference: Research to Practice 2016*. 14-16 April 2016, Melbourne, Australia

CHAPTER 1.

Introduction

1.1 Overview

This doctoral thesis contains five research studies that focus on 1) identifying the factors associated with success (i.e. victory) under the current, subjective system of judgement in competitive amateur boxing, in addition to 2) determining the factors that influence punch force production in highly-trained amateur boxers, and 3) investigating the effect of fatigue on both of these foci. Specifically, the first (field-based) study describes technical, behavioural, and perceptual characteristics of winning and losing boxers during National Championship competition bouts under the current subjective judgment system. In the second (methodological) study, a laboratory-based punch performance test that used a custom-built punch measurement tool was designed and validated. The third (laboratory-based) study examined the relationship between upper- and lower-body muscular strength and power characteristics on the ability to produce punch force in highly-trained boxers. Finally, the fourth and fifth studies separately examined the fatiguing effects of both competition boxing and intense lower-limb and trunk exercise on punching performance in highly-trained amateur boxers.

1.2 Background

Boxing is a popular Olympic and professional sport practiced by males and females all over the world [1]. Currently, competitive amateur boxing bouts such as those used in Olympic boxing are judged using the "Ten Point Must-System" (TPMS), which comprises three subjective criteria: 1) the number of quality blows on the target area, 2) domination of the bout by technical and tactical superiority, and 3) competitiveness [2]. Given that limited research has investigated the performance characteristics of amateur boxing competition under the TPMS, the technical and tactical actions that are associated with success are still largely unknown. It is understood that boxers must satisfy the judging criteria by exerting dominance and superiority over their opponent, or punching with sufficient force that the opponent is negatively affected, in order to be successful. Current literature suggests that successful boxers land more punches than their opponent and make use of straight-arm punches under the TPMS, however ~20% of the judge-determined winners are not those who landed the most punches [3]. As such, the subjective nature of the judging system means there is the enormous potential for observational cues other than the total number of punches landed to affect a judge's perception of dominance. However, observational cues and behaviours that might affect a judge's perception of dominance have not been investigated specifically, nor have there been considerations made regarding the potential effect of fatigue on such cues and behaviours.

Punch impact force has been identified as crucial for boxing success, regardless of the scoring system that is used in competition [4, 5]. Various measurement tools and test protocols have been implemented to assess punch impact forces within research studies, which makes comparison of results challenging, although several themes have emerged. The results of previous research consistently show that a boxer's level of expertise is positively related to the peak punch force they can produce [6, 7], which indicates that punch technique might be important for the production of high levels of punch force. Conversely, the role that physical strength plays in the generation of punch force is still unclear. Previous studies report indirect links between physicality and punch force production [8-11], although only one study [12] reported strong correlations between muscular strength and power characteristics in the upper and lower body and punch force production. While preliminary evidence shows that a boxer's force production capacity is associated with punch impact force, previous research does not reveal whether a boxer's peak strength, ability to produce force at high movement speeds, or the rate at which they can produce force (i.e. rate of force development) are key factors for producing high punch impact forces. Moreover, whether force production capacity of upper versus lower body musculature is most important for punch force production is still unknown.

Finally, while limited research has described the performance demands of amateur boxing bouts under the TPMS, the effect of fatigue on competition boxing performance has not been investigated, and it remains unknown how muscular fatigue impacts punch force production. Previous (non-boxing) literature has indicated that fatigue may alter behaviours, tactics and technical actions used by elite athletes in competition [13-15]. The potential effect of fatigue is particularly important under the subjective TPMS, given that there is the potential for any action performed in the boxing ring to influence the judges' perceptions of dominance and hence the outcome of the bout. Furthermore, fatigue could also impede a boxer's ability to deliver forceful punches during a competitive bout, and thus reduce their likelihood of gaining success over their opponent. However, the effect of fatigue on boxing performance has not been examined in previous research, and these hypotheses remain untested.

1.3 Significance of the research

Performance profiles that are characteristic of success provide information that is essential for boxing coaches, athletes and sport scientists alike, to ensure that training programs and practices can be adequately designed and performed [16-18]. This knowledge is also important for informing tactical decisions made by boxers and their coaches during competitive bouts, however the literature relating to competition performance under the TPMS is limited. Moreover, the physical characteristics related to punch force production are also important to advise strength and conditioning practices [4, 19], although these have not been directly or adequately examined in previous research. Through the use of both field-based descriptive research and controlled laboratory-based intervention studies, the research contained in the present thesis addresses many of the limitations and gaps in previous literature. The research outlines behavioural and technical elements of competition boxing performance under the TPMS and provides the first evidence to suggest that judge perception is influenced by both behavioural and technical elements. As such, both behavioural and technical variables are important to consider when preparing for competitive bouts. In addition, this research provides important findings relating to the physical characteristics associated with the production of high punch impact forces as well as describing the effect of both boxing-specific and non-specific fatigue on punch force production in highly-trained boxers. In doing so, this research provides information that can be used to improve strength and conditioning training recommendations related to maximising punch force production. Finally, the research contained in this thesis provides insights into the pacing profiles used, and the interaction between punch force production and behaviour change related to fatigue throughout a competitive boxing bout. The findings provide further information for adequate conditioning practices to be designed, such that boxers are able to withstand the possible fatiguing effects of a competitive boxing bout, in addition to describing behaviours and tactical strategies that are related to success in amateur boxing.

1.4 Research aims and hypotheses

The five sequential studies in this thesis investigate the competition demands prescribed by a subjective judging criteria. This thesis also aims to validate a laboratory-based performance test relevant for amateur boxers, and thereafter examines physical characteristics related to punch force production and the effects of targeted muscular fatigue versus boxing-specific fatigue on the ability to produce punch force. More specifically, the studies presented in this thesis aimed to investigate:

1.4.1 Study 1

Human behaviours associated with dominance in elite amateur boxing bouts: A comparison of winners and losers under the Ten Point Must-System (Chapter 3)

i. the changes in technical and behavioural actions over three rounds of elite boxing competition; and
ii. how boxers' perceptions of effort and fatigue vary throughout three rounds of elite boxing competition.

Hypothesis:

i. experiencing fatigue, or the demonstration of behaviours which indicate potential fatigue, during a competitive bout would affect the boxer's behavioural and technical actions, which could in turn affect the judge's perception of who was the dominant boxer.

1.4.2 Study 2

A damaging punch: Assessment and application of a method to quantify punch performance (Chapter 4)

i. the mechanical accuracy and reliability of a custom-built punch measurement tool (the punch integrator); and
ii. the reliability of a new laboratory-based boxing-specific punch performance test to assess, in detail, punch performance over a 3-min work period.

1.4.3 Study 3

Relationships between punch impact force and upper- and lower-body muscular strength and power in highly-trained amateur boxers (Chapter 5)

i. the relationship between muscular strength, power and rate of force development attributes of the upper and lower body as well as punch performance in a sample of highly-trained amateur boxers.

Hypothesis:

i. significant and positive relationships would be found between punching performance and the upper- and lower-body muscular strength and power characteristics of highly-trained boxers.

1.4.4 Study 4

The effect of fatiguing lower-body exercise on punch impact forcers in highly-trained boxers (Chapter 6)

i. the effect of a high-intensity fatigue-inducing bout of predominantly lower-body and trunk musculature (induced by machine rowing exercise) on punching performance in highly-trained male boxers.

Hypothesis:

i. the capacity to produce force with the lower body would be impaired by fatigue and therefore punch force would be significantly impaired.

1.4.5 Study 5

The effect of competitive boxing versus non-boxing fatiguing exercise on punch impact forces in highly-trained amateur boxers (Chapter 7)

i. the effect of competitive boxing bouts versus high-intensity fatigue-inducing lower-limb and trunk exercise (rowing) on punch performance in highly-trained amateur boxers.

Hypothesis:

i. whole-body fatigue (shown by changes in heart rate, blood lactate concentration and rating of perceived exertion) induced by rowing, that is physiologically similar to the levels previously observed during boxing competition, may impose a similar threat to punch force production.

1.5 Definitions of selected terms

Δ	Delta; change
%Air	The number of air punches (Air) expressed as a percentage of total punches
%Hit	The number of hits (Hit) expressed as a percentage of total punches
%Miss	The number of misses (Miss) expressed as a percentage of total punches
%RFD	Rate of force development normalised to peak force
°C	Degrees Celsius
$[La^-]$	Blood lactate concentration
3MPT	3-minute punch test
AIBA	Association Internationale de Boxe Amateur/International Boxing Association
Air	A punch that does not make contact with the opponent
ANOVA	Analysis of variance
a.u.	Arbitrary unit
BOX	Boxing condition
bpm	Beats per minute
CI	Confidence interval
CL	Confidence limit
CMBT	Countermovement bench throw
CMJ	Countermovement jump
CON	Control condition
CV	Coefficient of variation
d	Cohen's *d*
ES	Effect size
F	F-value or F-ratio
F	Force in newtons (N)
F_{5ms}	Punch force reading 5 ms after the start of punch contact
F_{10ms}	Punch force reading 10 ms after the start of punch contact
h_{cmj}	counter movement jump height
HF	High punch force group
Hit	A punch hitting the target of the opponent
HR	Heart rate
Hz	Hertz
IBP	Isometric bench push
ICC	Intraclass correlation coefficient
IMTP	Isometric mid-thigh pull
kg	Kilogram

kPa	Kilopascal
LF	Low punch force group
MANOVA	Multiple variable analysis of variance
MF	Medium punch force group
min	Minute(s)
Miss	A punch that makes contact, but misses its target area of the opponent
$mL \cdot kg^{-1}$	Millilitres per kilogram
$mL \cdot kg^{-1} \cdot min^{-1}$	Millilitres per kilogram per minute
$mmol \cdot L^{-1}$	Millimoles per litre
ms	Milliseconds
N	Newtons
$N \cdot kg^{-1}$	Newtons per kilogram of body mass
N·s	Newton seconds
$N \cdot s^{-1}$	Newtons per second
P	Power in watts
p	p-value
PI	Punch integrator
r	Pearson's correlation coefficient
R^2	Coefficient of determination
r_s	Spearman's Rho
RFD	Rate of force development
ROW	Rowing condition
RPE	Rating of perceived exertion
s	Seconds
SD	Standard deviation
SWC	Smallest worthwhile change
$t_{F10\%}$	Time taken to reach 10% of the peak punch force
$t_{F50\%}$	Time taken to reach 50% of the peak punch force
$t_{F90\%}$	Time taken to reach 90% of the peak punch force
$t_{F50-90\%}$	Time between 50% and 90% of the peak punch force
t_{200N}	Time taken to reach 200 N of punch force
t_{500N}	Time taken to reach 500 N of punch force
TE	Typical error
TPMS	Ten Point Must-System
VHM	Vertical hip movements
W	Watts

CHAPTER 2.

Review of literature

2.1 Overview

This review of literature provides information relevant to the studies of this doctoral thesis. Specifically, this chapter outlines research reported in peer-reviewed manuscripts relating to the demands of competitive amateur boxing performance, and the physical and physiological characteristics of elite male amateur boxers.

2.2 Introduction to amateur boxing

Boxing is a popular, full-contact striking combat sport with a long history. The earliest historical reports of boxing appeared in Ethiopia as early as 6000 B.C. [1]. Amateur boxing was first included in the modern Olympic Games in St Louis in 1904, and was permanently added to the program in Antwerp in 1920 [1]. The international governing body for amateur boxing, AIBA (Association Internationale de Boxe Amateur/International Boxing Association), sanctions contests for males and females within 10 weight categories for each sex (ranging from 46kg to over 91kg and 45kg to over 81kg for males and females respectively). In 2001, the first AIBA Women's World Boxing Championship was held in Scranton, USA. Eleven years later, the 2012 London Olympics debuted three female weight categories to accompany the 10 men's categories [20]. The popularity of male and female boxing continues to grow, and the upcoming 2020 Olympic Games in Tokyo is set to include eight male and five female weight categories. As such, a total of 52 Olympic medals will be contested in Tokyo by boxing athletes alone.

During boxing competition, contestants aim to deliver clean, forceful punches to their opponent without being punched in return. Throughout its history, like any sport, amateur boxing has undergone many adjustments with respect to rules and regulations [20]. In 2009, significant changes to the bout format and method of judging were implemented in amateur boxing competition whereby the bout format for male boxers changed from four 2-min rounds (4 × 2 min) to three 3-min rounds (3 × 3 min) with an unchanged rest period of 1 min between rounds. In 2013 head guards were removed from male competition (but remained for female and youth boxers), and the scoring system changed from a computer-based punch counting system to the "Ten Point Must-System" (TPMS; i.e. judges "must" award 10 points to the winner) for all AIBA contests [2]. Further to this, in 2017, AIBA changed the female competition format so the males and females both contested 3 × 3-min rounds [21]. Under the previous, computer-based scoring system, boxers would aim to score more points than their opponent by punching the target area of the opponent (on or above the line of the belt on the front of the torso, and the front and side of the head) with sufficient force for the judges to notice the contact [3]. Judges would press buttons (red or blue) when they believed a scoring punch had landed, and if three out of five judges registered a point for the same boxer within one second then the point was awarded; the boxer with the most points at the completion of the bout was awarded the winner. This scoring system was deliberately objective to minimise judge bias after suspected corruption arose in 1992 [20]. In contrast, the TPMS (also referred to as "must" or "impression" scoring) is a subjective judging system in which judges assess boxers based upon three criteria: 1) the number of quality blows on the target areas, 2) domination of the bout by technical and tactical superiority, and 3) competitiveness [2]. The TPMS was implemented to minimise single punch tendencies of boxers and create a contest that was "more spectacular" [20]. According to the judges' perceptions of the boxers in relation to these criteria, they award 10 points to the winner of each round and between seven and nine points to the loser, depending on how close the contest is perceived to be [2]. Under both judging systems, boxers could still defeat their opponent by knockout or knockdown, when boxers deliver a strike that causes a loss of consciousness, or a temporary incapacitation to the opponent such that the referee stops the bout, or calls a stop for the count of eight (referred to as an eight-count).

The majority of research examining performance aspects of amateur boxing has been conducted with male boxers under either the computer-based scoring system or the TPMS. However, even though a change in competition rules can have significant effects on the performance demands and tactics of a contest [1, 20], a surprising amount of literature examining official or unofficial competition did not explicitly state under which scoring system the data were collected, making it difficult to determine whether the conclusions from the research are relevant under the current scoring system. Thus, the present review of literature will focus on four key areas of research relating to: 1) the components of success in amateur boxing competition under the TPMS, 2) the physical and technical components of producing punch force, 3) the effect of fatigue on amateur boxing performance, and 4) the limitations of current research.

2.3 Successful amateur boxing

The strict rules and regulations of amateur boxing competition present a challenging environment in which to analyse amateur boxing performance. Researchers have previously acknowledged that the collection of physiological and performance monitoring data during official boxing competitions is difficult [22, 23]. This is due to the fact that the coach and assistant are the only personnel allowed to mount the apron (field of play) during breaks between rounds and there is strict control in regards to apparel and protective equipment permitted for use [2]. Accordingly, the collection of quantitative information via tracking and monitoring devices (e.g. inertial sensors, global position system [GPS] trackers or heart rate monitors) is not permitted. As a result, several studies have utilised performance analysis techniques (e.g. video capture for later analysis of boxer movement patterns) with the purpose of describing physical and technical patterns used in competition. The majority of previous research comparing winners to losers in this way has been conducted under the computer-based scoring system [22, 24, 25] and may not be completely applicable to performances under the TPMS. The following section therefore compares findings related to successful amateur boxing performance under the computer-based scoring system and the TPMS.

2.3.1 Computer-based scoring system

The computer-based scoring system required boxers to score points by landing punches with sufficient force on the specified target areas. The boxer with the most points at the conclusion of the bout was declared the winner. Judges would award points to the boxers when they saw a scoring punch or, when the boxers were fighting in close proximity to each other, one point would be awarded to the boxer who is deemed most successful. Points could also be deducted at the discretion of the referee or judges if a boxer infringed upon the rules [26].

Under the computer-based scoring system, three performance analysis studies reported that winners and losers in elite male competitions threw a similar number of punches in total (53 - 65 per round), however winners showed greater accuracy and landed significantly more punches than losers [22, 24, 25]. In addition, all three studies reported that winners used fewer defensive actions than losers, although no strong rationales were proposed to explain this observation. Moreover, straight arm punches such as jabs (lead hand) and crosses (rear hand) were found to be most frequently thrown whilst uppercuts were least used, which was attributed to the preference of boxers to maintain some distance between themselves and their opponent [25]. Davis et al. [22] and El-Ashker [24] speculated that the uppercut might be the most technically difficult punch to execute and that this might underpin its infrequent use. By contrast, Thomson et al. [25] speculated that boxers would have to position themselves close to the opponent to use the uppercut, which might increase their risk of being struck in return and therefore boxers did not employ the punch frequently. Not surprisingly, landing more punches in addition to using a greater number of offensive actions and fewer defensive actions were characteristics of winners under the computer-based scoring system.

In addition to citing the number and types of punches used by boxers, Davis et al. [22] provided information relating to clinching, referee stoppages and movement style (measured by counting vertical hip movements; VHM, i.e. bouncing) as well as the specific punch types, landing locations and measures of success. These variables were included with the aim of providing information relating to the possible physiological cost (energy expenditure) of boxing. However, their inclusion also provided a novel platform on which to assess behavioural differences between winners and losers, and thus whether they were associated with fight dominance. Furthermore, they allowed speculation as to the possible accumulation of fatigue during the bouts. One interesting finding was that ~14% of judge-determined winners were not the boxers who landed the most punches, even though the judges were using the computer-based scoring system. While some authors [22, 27] acknowledge that this should not be considered as 'misjudging', the result could reflect conscious or subconscious judge bias, the latter of which might speculatively be related to what a judge perceives as a display of dominance. Nonetheless, it was not possible in these studies to determine whether judges' subjective perceptions of fight dominance influenced their scoring decisions (and thus the bout winner). Therefore, while it was clearly stated that landing punches is the most important factor for success under the computer-based scoring system, these data suggest that more complex factors that alter the judges' perceptions about each boxer may play a role in a boxer's success.

While these studies have provided an initial foundation of knowledge, there are some methodological issues that must be acknowledged. One possible issue in the study of El-Ashker [24] is that the "winner" and "loser" in each bout were determined by the number of punches landed during the post-hoc fight analysis rather than the result determined by the judges. Therefore, it is not clear whether there were discrepancies between the boxers that were declared the winner by the analyst compared to the judges, and thus whether the boxers were analysed in the correct category (winner or loser). The likelihood is that at least some of the boxers declared the winner in the study were not awarded victory by the judges, given that Davis et al. [22] reported that ~14% of actual bout outcomes did not align with the number of punches landed. In addition, the inter-tester reliability analysis was conducted on only 6 out of 19 easily identified variables, including the number of punches thrown and landed. This is problematic since these variables may not be reflective of all variables analysed, some of which may be more difficult to identify, such as punch type and defensive actions used. Finally, given that analysis was performed on semi-final and final bouts of a tournament, the 22 boxers who contested the final bouts were also analysed in their semi-final bout, which is likely to have introduced bias into the results (i.e. 22 boxers of 44 were analysed twice to achieve a sample of 66). In the study by Davis et al. [22], inter-tester reliability was not determined to confirm the reproducibility of the methods, and 19 of 39 boxers were included twice in the analysis to achieve a sample size of 58. Thus, while these studies provide important information relating to the performance profiles of winning and losing boxers, certain methodological issues, in addition to the use of data from competitions that were judged under the computer-based scoring system, means that further examinations are needed to determine the technical and tactical characteristics associated with winning under the TPMS.

2.3.2 Ten Point Must-System (TPMS)

The TPMS system of judging is currently implemented in amateur and professional boxing competition. The rules require boxers to exert dominance over their opponent according to three subjective criteria: 1) the number of quality blows on the target area, 2) domination of the bout by technical and tactical superiority, and 3) competitiveness [2]. While the judging criteria have been explicitly stated, specific definitions of the terms used in the criteria are not specified in detail. Thus, there is significant subjectivity as to how to use the criteria. For example, the first judging criterion (the number of quality blows on the target area) involves a subjective assessment of what constitutes a “quality blow”, and the second and third criteria require the judges’ subjective perceptions of “domination”, “superiority” and “competitiveness”, which could vary substantially between judges.

Davis et al. [22] acknowledged that the findings of the (objective) computer-based scoring research became less relevant, as the change to the (subjective) TPMS was likely to have affected the demands of the contest. Consequently, Davis et al. [3] analysed activity profiles of elite boxers under the TPMS and found that total activity rate increased from 1.4 actions per second (under the previous judging system) to 1.9 actions per second, and that an increase in the amount of VHM (i.e. bouncing) was observed in all boxers. Under the TPMS there were fewer variables that could discriminate between winners and losers; winners landed more punches and used straight punches more than losers. The frequency of offensive and defensive actions remained similar under the TPMS and winners and losers used similar numbers of offensive and defensive actions. Of interest is that the percentage of bouts in which the winning boxer did not land the most punches increased to ~20% under the TPMS (i.e. from 14% under the computer-based system), which was attributed to winners using more straight punches to keep their opponent at long range. Nonetheless, this study provides the first evidence that the subjective judgments inherent in the TPMS promotes the consideration of factors that are not easy to objectively quantify, and thus can depend on a judge's perception of loosely defined terms outlined by the international governing body, AIBA. However, a drawback of the study is that the authors used the same methods as in the previous studies highlighted above [22], including the use of data collected on multiple occasions for some (typically winners) but not other (losers) boxers. These data provide initial evidence that successful boxing performance under the TPMS is linked to judge perception, however specific actions, behaviours or styles of boxing that may be perceived as "dominant" are not known.

Given that the literature discussing the TPMS in amateur boxing is limited to the single study published by Davis et al. [3], an understanding of how judges perceive dominance and superiority in the context of boxing still poses a complex challenge for researchers and boxers alike. Nevertheless, understanding how winners are chosen under the new system is important to provide a template for success in amateur boxing, and can inform the training practices of boxers. In addition, from a broader perspective, researchers and boxers may draw comparisons from other, similarly-judged combat sports [28-30] or, even more broadly, from literature describing the behaviour of primates fighting for dominance in the wild [31, 32], to understand fighting for subjective dominance. There are numerous social and physical advantages associated with a display of dominance through physical confrontation in the wild [32, 33]. As such, the instinct to assert and perceive dominance is still evident in humans within modern society [34-37]. From this view, combat sports are a unique opportunity to study humans fighting for viewer-perceived dominance. Aside from a knockout or debilitating blow, a blue print of dominant behaviour has not been developed for the modern combatant. However, research examining success in Mixed Martial Artists has reported that seemingly unrelated traits, such as facial features, voice, perceived masculinity, and aggression are associated with the outcome of sanctioned fights [28, 29, 38, 39]. In light of these findings, the perception of superiority, dominance and competitiveness of amateur boxing judges under the TPMS is unlikely to be limited to their observations of boxing-specific actions. Thus, there is the potential that any trait or action performed in the ring could influence the judges' perceptions of dominance, and influence the result of the bout.

2.3.3 Physiological demands of amateur boxing

Several studies have described the physiological demands of amateur boxing. Given that there is the potential for every action (either technical or behavioural) to be assessed by the judges under the TPMS, descriptions of the physiological demands and fatiguing effects of competition boxing are particularly important. Several studies have previously reported on physiological variables during boxing bouts [5, 11, 27, 40-45] or simulated competitive boxing [23, 42, 46-52]. The combative nature of boxing means that it is not possible to acquire measurements of oxygen consumption during a bout, given that the head and face are a target region that can be attacked. As such, data collected during bouts is limited to variables such as heart rate (HR) and blood lactate concentration [La^-], which can be measured in the breaks between rounds or at the conclusion of the bouts. Previous literature has shown that the current 3 × 3-min bout format elicits a significant cardiac response and results in high concentrations of lactate in the blood. Throughout competitive bouts, HR has been shown to increase significantly, with peak HRs of 187 - 191 bpm (approximately 93% of maximum HR) recorded after the final round [11, 41]. Similarly, [La^-] increases significantly in each round with peak readings of 8.9 - 17.0 $mmol \cdot L^{-1}$ at the conclusion of a bout, although this range appears to narrow to 8.9 - 13.6 $mmol \cdot L^{-1}$ when boxers have tapered for competitive bouts [11, 40, 41]. These studies provide novel and important insight to the physiological demands of competitive boxing, although the methodological limitations caused by the restrictions regarding data collection during official bouts are likely to have resulted in a significant underestimation of the total energy cost of amateur boxing.

Various simulated boxing protocols that do not involve any interaction between boxers (so they cannot be punched) have been implemented in order to overcome the strict competition rules, and provide an opportunity to directly measure heart rate response and oxygen consumption throughout a boxing-specific exercise bout [23, 48, 49, 53]. Studies have used various 3 × 3-min boxing simulations that involve standardised punching combinations performed on a fixed punching bag, hand-held focus pads, or exercise bouts on focus pads that were controlled by a coach, to mimic the activity patterns of competition boxing bouts (work rates of 17.5 - 26.8 punches/min). In another case, oxygen consumption was measured in the rest period between simulated bouts where boxers sparred each other inside a laboratory. As in competitive bouts, peak HR during boxing simulation protocols increased as rounds progressed and ranged 169 - 196 bpm [23, 48, 49, 53], and [La^-] ranged 4.3 - 12.5 $mmol \cdot L^{-1}$ after the efforts [23, 53]. While some [La^-] measures were much lower than in competitive boxing, Finlay et al. [23] reported that [La^-] increased significantly in each round. Similarly, the rating of perceived exertion (RPE) has been shown to increase significantly in each round during boxing simulations [23, 49]. In contrast, peak oxygen consumption (43.8 - 55.3 $mL \cdot kg^{-1} \cdot min^{-1}$) was previously observed to show no increase over the three rounds of a competitive bout [23, 48], while the total oxygen consumption (123 - 132 $mL \cdot kg^{-1}$) was observed to be greatest in the second round of a simulated boxing bout [49]. In that sense, simulation protocols have been shown to be similar in some (but not all) respects to competitive boxing bouts. Further, it is likely that measures taken during boxing simulation protocols underestimate the total energy cost of amateur boxing. Nonetheless, these studies collectively show the physically demanding nature of amateur boxing in the 3 × 3-min format, and highlight that boxers must be sufficiently conditioned to be able to successfully box at a high level for the whole duration of the bout [1, 54]. Given the strenuous demands associated with boxing, the likelihood that boxers experience significant physiological fatigue during competition and training bouts is high. The extent to which fatigue affects a boxer's ability to perform under the TPMS, and the subsequent effect on subjectively-based bout outcome is not known.

2.4 Punch force in boxing

The method of judgement as well as the competition rules implemented in amateur boxing have the potential to change the behaviours or tactical decisions that boxers make in training and competition. However, success in amateur boxing competition can be gained by punching the opponent with sufficient force such that they are knocked out, knocked down, or their fighting ability is negatively affected, regardless of the scoring system. Indeed, the ability to deliver a punch with a high impact force may allow a boxer to physically knockout the opponent, or to influence the judges' perceptions with the visual effect of a forceful punch landing 'cleanly'. As such, a well-directed forceful blow that causes the opponent to be thrown out of their boxing stance or form, or their body or head to be briefly knocked backwards, is likely to be perceived as favourable by the judges as a display of bout domination. Moreover, should the blow result in a brief period of incapacitation or brief loss of consciousness, the referee may award an eight-count, or in some cases a knockout or knock down may occur, all of which are ways to gain success in a competitive bout. Accordingly, the capacity to produce punch force is a key component of boxing competition and has received much attention throughout boxing sport science literature [4-9, 11, 12, 55-62].

One noteworthy study examined forces applied during six professional boxing bouts [61]. Force was measured by a sensor embedded in each boxer's gloves, with data transmitted to a ringside computer for interpretation. The data indicated that the boxer who applied the greater cumulative force to the opponent over the duration of the bout was always awarded the winner, supporting the hypothesis that punch force is important for success. The results of that study also showed that the force applied per punch in a boxing bout was less than that applied in a laboratory setting (which is discussed later in this section). However, this conclusion was based on only four bout results, as one bout was stopped prematurely without a decision and another resulted in a draw. Additionally, one bout of the four that had a clear result ended by knockout in the first round, thus, less than one round from this bout could be analysed. This resulted in a small pool of data on which to base conclusions. While data collected in real boxing bouts are valuable, the tool used to measure punch force, the *bestshot* System™, contained a sensor that was not validated in the context in which it was used, thus the mode reliability and accuracy of the system was difficult to determine [63]. Moreover, the weight categories (60 - 91 kg) and experience of the boxers involved in the study varied greatly, with one participant boxing in their first professional bout and another in their 50th. This study provides interesting information relating to the forces applied during a boxing bout, however the findings should be interpreted with caution given the aforementioned concerns regarding participants and methodologies used.

Two other noteworthy studies pioneered the laboratory-based measurement of punch force [59, 64]. The first, by Atha et al. [59] analysed one maximal punch (the punch type remained undefined) from a English professional heavy-weight boxer and reported that the force of one blow was 4096 newtons (N), which was estimated to be approximately 6320 N when delivered to the head. This study utilised an instrumented, padded target mass suspended as a ballistic pendulum that contained a piezoelectric transducer positioned between the punching surface and the 'centre mass' of the device. Even though the sample included only a single professional boxer, this was the first study to use sophisticated measurement techniques and describe the methodology thoroughly. The other significant study reported that increased mastery of boxing was associated with greater lower-limb force contribution (38%) to total punch force [64]. In contrast to the study by Atha et al. [59], the methods reported in this study by Filimonov et al. [64] provided insufficient detail regarding measurement tools, methods of data collection, calculations and analyses performed in the study. Furthermore, comparisons of punch forces were made between boxers that were described as Masters of sports and Candidates for Masters of sports, Class I and Class II and self-described “knockout artists”, “players” and “speedsters”, although the descriptions of these groups were not sufficient to allow replication. Furthermore, the magnitude of punch force produced by each group was not reported. Despite the questionable validity of the data, the findings of Filimonov et al. [64] provided the preliminary reports suggesting that, in general, technique and physical strength might be important factors influencing punch impact force, and that the lower-limb musculature may be key to punch force production. However, specific elements of technique and physicality that are relevant for increasing the force in a punch were not identified.

Throughout the literature that examines punch delivery, punch impact forces of 761 - 4800 N have been obtained by using a wide variety of measurement tools and protocols in different populations of boxers [7, 60, 62]. Comparisons between weight classes, expertise levels, punch types (e.g. lead- versus rear-hand punches), and sexes, as well as external factors that might influence punch force delivery (such as performance feedback or energy availability) have been investigated. Throughout the literature, a core of consistent findings has been obtained that relate to either punch technique or the physical characteristics of the boxer.

2.4.1 Technical elements of punch force production

Several areas of research exist relating to effective punch technique [65], the relationship between punch impact forces and expertise level [7], and punch impact forces delivered under various test conditions [66]. However, research that directly measures punch impact force and describes specific punch techniques associated with such forces has not been conducted. As a result, studies that report on either punch impact forces or punch technique can provide indirect evidence supporting the positive relationship between punch technique and punch impact force.

Several research studies have observed that boxers with greater levels of expertise punched harder than those with less experience [6, 7]. Joch et al. [6] reported rear-hand straight (cross) punches delivered to a fluid filled punching bag containing a pressure sensor were equal to 3453 N for elite-, 3023 N for national- and 2932 N for intermediate-level boxers. However, the reliability and error of the system was not reported. Smith et al. [7], utilised a reliable and valid boxing dynamometer (four wall-mounted triaxial piezoelectric force transducers [Kistler Instruments, 9366AB] that sampled at 330 Hz, positioned behind a padded punch surface shaped as a human torso) to measure punch force. They reported impact forces for jabs and crosses in elite- (2847 ± 594 N and 4800 ± 601 N, respectively), intermediate- (2283 ± 355 N and 3722 ± 375 N, respectively) and novice- (1604 ± 273 N and 2381 ±328 N, respectively) level boxers. Smith et al. [7] also found a significant difference between the force applied in the lead hand (jab) compared to the forces delivered in the rear hand (cross). This finding was reproduced in several other studies [5, 56] with high quality measurement tools, such as the tools described by Smith et al. [7]. The boxing dynamometer had good reliability (coefficient of variation < 1%), stability (< 1% drift), as well as sufficient sensitivity to discriminate between three skill levels of boxers. However, given that punch impact occurs over a very short period of time, the low sampling rate may have acted as a lower-pass filter, reducing the likelihood of determining the true peak and thus limiting the resolution of the system. Together, findings indicate that punching technique, which may be assumed to be better in boxers of a higher level and is very different between lead and rear hands, is important for producing high peak punch forces [5-7, 56].

One study that examined muscular recruitment patterns during punching contributes further evidence to the hypothesis that punch impact force is affected by punch technique [58]. Electromyography has been used to quantify upper- and lower-body muscle activation patterns in punches delivered with maximum force versus maximum speed. Not surprisingly, punching with the intention to produce maximum force resulted in greater punch impact forces than punching for maximum speed [58]. The muscle activation patterns during punches delivered with both maximum force and maximum speed utilised a linear model of muscular recruitment (i.e. sequential recruitment of muscles originating from the legs, trunk, shoulders and arms; a throw-like movement pattern). However, punches delivered with maximum force were characterised by greater activation of gastrocnemius, rectus femoris, and biceps femoris muscles during the initial phase of the movement compared to punches delivered with maximum speed. These observations indicate that early muscle activation of the lower body is an important technical requirement to generate the momentum that is necessary to transfer through the kinetic chain and deliver to a punch target with great impact force [58]. Moreover, studies that have described punching technique (without measuring resultant impact force) report that punches that involve greater degrees of trunk rotation and leg drive (i.e. the cross, and hook punches) result in higher impact velocities [65, 67, 68] than punches that do not (e.g. jab). To this end, it may be inferred from the collective, but indirect, evidence [6, 7, 58, 69] that punch technique is, to a certain extent, responsible for the level of punch force produced by boxers.

2.4.2 Physicality and punch force production

An alternative hypothesis that might at least partly explain differences in punch force production between expert and non-expert boxers is that experts may be physically stronger than less experienced boxers, and thus that physical strength is a key determinant of punch force production. As lower-limb muscle activation in the early stages of a punch appears to be an important factor influencing punch force [58], and a high-speed punch requires use of a throw-like kinetic chain pattern (i.e. commencing with the lower-body and ending with arm extension), one might speculate that the strength of lower-limb musculature might influence peak punch force production.

Several studies have reported punch impact forces during various stages of competition preparation or throughout physical conditioning programs. Two studies used a common punch force assessment tool and study design and found that 4-week training interventions that targeted “explosive strength, speed strength and speed abilities” of the upper and lower body, and upper- and lower-body plyometric training improved punch force for some punch types (cross and “low punches”, and “low punches”, respectively [8, 9]). While good between-day reliability (intraclass correlation coefficient; ICC > 0.95) for single maximal punches was reported, the measurement tool and protocol were not adequately described so it is unclear exactly how the testing was completed, and the validity and accuracy of the system were not confirmed [8, 9]. Two more studies reported relationships between physical characteristics and punch force production by monitoring both of these factors during different training phases. A case study showed that punch force production (single maximal jabs, crosses, lead- and rear-hand hooks) and muscle function (tested by countermovement jump; CMJ, isometric mid-thigh pull and isometric bench-press) followed similar patterns of change during an 8-week competition preparation period [10]. Similarly, Hukkanen and Häkkinen [11] found that punch force (in jabs and crosses) in national-level Finnish boxers was reduced in the competition versus preparation training period. Both studies attributed their findings to the different training volumes and intensities during preparation and competition periods [10, 11]. Collectively, these studies provide evidence that the physical strength and power of a boxer is related to their ability to produce punch force [8-11], and together with the evidence relating to punch technique (discussed in the previous section [6, 7, 58, 69]) suggest that strength in the lower limb might be a key physical component for producing high punch impact forces.

Although the evidence presented thus far indirectly indicates that punch force might be influenced by a boxer's physical capacity, and very likely their lower-body strength, only one study to the author's knowledge has directly examined this relationship. Loturco et al. [12] correlated punch force production in the lead- and rear-hand punches (jabs and crosses) with various measures of upper- and lower-body strength and power (tests included the bench throw, bench press, CMJ, squat jump and isometric half squat) in international-level Brazilian male (n = 9) and female (n = 6) amateur boxers. Significant correlations (r = 0.69 - 0.85) were observed between peak punch force in the jab (male = 1152 ± 246 N, female = 933 ± 164 N) and cross (male = 1368 ± 266 N, female = 987 ± 192 N) punches and several physical characteristics including jump height in squat jump and CMJ, mean propulsive power in the squat jump, bench throw and bench press, and mean isometric force measured in the half squat position. These data constitute the first direct evidence indicating a relationship between punch force application and muscular strength and power. Loturco et al. also found that male boxers punched with significantly more force and were significantly stronger (according to muscular strength and power tests) compared to female boxers. Given that the boxers were of a similar high skill level, the differences reported in punch force were probably explained by different muscular strength and power characteristics related to sex [12]. However, the sex-related differences in physical strength introduced high between-subject variability which may have led to correlation coefficient inflation. As such, the importance of some physical strength and power attributes may have been subsequently over estimated, and thus there was inadequate discrimination between physical attributes that were and were not related to producing high punch forces.

Various direct and indirect reports indicate that muscular strength and power characteristics [8-11], in addition to punching technique [6, 7, 58, 69], are associated with the production of high peak punch force. However, only one study (in a heterogeneous sample of boxers [12]) has directly examined the relationship between physical strength and punch force production. While the findings provide evidence that physical factors are important for punch force production there were no discriminating physical characteristics found. As such, there is no direct evidence to support the hypothesis that lower-body strength and force production are key factors for producing high punch impact force. Furthermore, the specific strength and power characteristics of the upper and lower body that have the potential to increase punch force production have not been determined by previous research.

2.4.3 Other factors influencing punch force production

In addition to the studies that have examined punch technique or muscular strength and power, numerous other studies have reported a positive relationship between body mass and punch force production [6, 12, 70]. These data suggest that a greater muscle mass may benefit punch force production, since fat mass is typically low in boxers [1, 5]. Nonetheless, given that boxers compete in weight categories, increasing mass as a means to increase punch force capacity is rarely feasible unless the boxer is willing to compete in a heavier weight category [71]. It is also worth considering that, when measured during competitive bouts using the *bestshot* System™ (rather than measuring using a force platform/system in a punching test), it was found that heavier boxers did not necessarily punch harder than lighter boxers [61]. However, it is important to consider that these results are not reflective of maximal punch capacity but instead reflect tendencies during competitive boxing when punches are thrown at a moving human target.

Additionally, numerous studies have assessed the effect of external factors or conditions on a boxer's ability to produce punch force. Previous research has shown that punch force is generally greater when boxers position themselves at a self-selected distance from the punch target [12], and when they punch with the intention of exerting maximum force versus maximum speed [56]. In addition, a 4-week β-alanine supplementation program has been reported to increase punch force production in amateur boxers [53]. Conversely, false-positive, false-negative and neutral feedback have been reported to have no effect on punch force production in elite boxers [72], and restricting fluid and energy intake (practices that are associated with rapid weight loss before a weigh-in) had no effect on punch force production [57]. These findings provide useful information for coaches and boxers regarding the use of coaching cues and weight-cutting practices, although there are still many factors that have the potential to influence amateur boxing performance and are worthy of investigation; for example, specific research examining the effect of fatigue on boxing performance.

2.5 The effect of fatigue on amateur boxing performance

An area of research that is important to consider, but has received little attention, is the potential effects of fatigue on boxing performance. The strenuous physical nature of boxing (discussed previously in this chapter) highlights that fatigue may affect boxers during training and competitive bouts [1, 54]. The potential effect of fatigue in amateur boxing is twofold. Firstly, fatigue may affect a boxer’s capacity to produce high levels of punch force, which has been shown to be important for success in amateur boxing [4, 5]. Secondly, fatigue may affect how a boxer behaves in the boxing ring, which under the TPMS may affect the judge’s perception of the boxer’s performance and thus influence the result of the bout.

Few studies have investigated these hypotheses. One study observed a significant performance decrement in the second bout of two 5 × 2-min boxing bout simulations performed on a punch force dynamometer [55]. This was regardless of whether or not boxers received a massage intervention designed to enhance recovery in the 20-min period between the repeated tests. On the contrary, another study reported no differences in single maximal punch forces when boxers performed with restricted or unrestricted (control) energy availability [57]. This result is consistent with several other studies from other sporting contexts, that observed the maintenance of task-specific outcomes despite athletes performing in a fatigued or otherwise compromised state [13-15, 73]. However, this literature suggests that an alteration in movement pattern or pacing strategy is usually required to maintain such outcomes [13-15, 73]. For example, the vertical component of acceleration during high-speed running has been shown to decrease when Australian Rules football players are fatigued despite the players’ running rates (metres per min and high-speed running metres per min) remaining the same [15]. Interestingly, this movement pattern (involving less vertical acceleration, i.e. becoming “flat”), is poorly perceived by coaches even though the outcome of the athlete’s performance did not change [15]. In a boxing context, several studies have observed the number of VHMs and clinches during competition boxing bouts, and interpreted changes in these variables as a manifestation of fatigue [3, 22, 27, 74]. This indicates that, like in many other sports, boxers may adopt behaviour-changing tactics during competition to mitigate the effect of fatigue on achieving a desired performance outcome.

The limited amount of research that specifically investigates the effect of fatigue on amateur boxing performance represents a significant knowledge gap. This gap is especially pertinent for performances under the TPMS where judge’s perceptive assessments of the boxers determines the outcome of the bout in most contests [20]. Given that in other sporting contexts the behavioural manifestations of fatigue may have negatively influenced the perceptions of external viewers, the effect of fatigue on boxing performance has the potential to be severe.

2.6 Limitations of current literature

As mentioned previously in this literature review, significant knowledge gaps exist concerning the effect of fatigue in amateur boxing performance. This is particularly important given that fatigue may affect the amount of force produced in a boxer's punch, which is an important factor of successful boxing performance. In addition, both boxing- and non-boxing-related research indicates that the manifestations of fatigue may be perceived poorly by judges under the TPMS. Therefore, it is crucial that future research examines the effect of fatigue on punch force production, and investigates behavioural indicators of fatigue in relation to boxing competition success under the TPMS.

2.6.1 Influence of a new judging system

Since the implementation of the TPMS in 2013, only one study has described the performance profiles of successful and unsuccessful boxers [3]. This study provides valuable insights regarding the technical and tactical approaches boxers apply to bouts under the new judging system, however other factors that may influence the judges' perceptions of dominance have not been described. Approximately 85% of bouts are decided by judges (i.e. rather than by knockout [20]), and given that 20% of the bout results could not be explained by the number of punches landed, there is evidence that judge perception of performance may be, in some cases, dictated by factors that are not easily quantified [3]. The influence of behavioural factors such as stylistic movement patterns, actions that indicate fatigue, or other cues that judges may perceive as indications of greater or lesser dominance are still unknown. Thus, future research should aim to identify and quantify these cues.

2.6.2 Assessing boxing performance

A limiting factor for many studies that have assessed boxing performance using notational analysis or by measuring punch force is the quality of the methodology used. Many studies do not provide sufficient detail about the methods used such that study replication is possible, and several studies that report punch forces do not report the reliability or accuracy of the measurement tool or protocol used for data collection, and therefore the usefulness of the findings are brought into question. These limitations, and the use of a wide range of testing methods within the literature, make comparisons between studies difficult [1, 75]. A limitation specific to studies that measure punch force is the use of low sampling frequencies during data collection (330 - 500 Hz [5, 7, 12, 55-58]) or the lack of reporting of data sampling frequency at all [6, 8, 9, 11, 59-62]. Given that punch forces of ~4000 N are applied in a duration of ~22 - 40 ms [69, 76], sampling at 330 - 500 Hz would allow the collection of only 8 - 20 data points during punch impact and may not have the sensitivity to accurately capture the peak force of the punch.

2.7 Summary and conclusions

A wide range of topics related to amateur boxing performance have been previously studied. However, after the implementation of the TPMS the performance requirements for success have received little attention by researchers. The available literature suggests that boxers must maintain a high level of punch accuracy and utilise straight punches during a competitive bout to be successful, [3]. Physical and physiological demands suggest that boxers must be able to maintain work rates of up to 1.9 actions per second, which requires well-developed aerobic and anaerobic systems. At an elite level, boxers must tolerate near-maximum heart rates as well as high blood lactate concentrations during competitive boxing bouts [11, 40, 41]. Furthermore, implementation of boxing simulation protocols has suggested that one round of boxing may incur an oxygen cost of up to 132 $mL \cdot kg^{-1}$ [23]. The influence of a boxer’s behavioural and stylistic actions on the perception of the judges is not known. Furthermore, the effect of fatigue on a boxer’s actions in the ring, and their ability to produce punch impact force, are currently unknown.

Delivering forceful punches has been identified as an important component of successful amateur boxing and has received a lot of attention in the literature. A wide range of punch forces have been reported in a variety of boxing populations. While these studies use several different punch force measurement systems, which can make comparisons challenging, some consistent themes have emerged. The literature shows that there is a positive relationship between a boxer’s level of expertise and punch impact force, with more experienced boxers punching with more force than less experienced boxers [6, 7]. In addition, male boxers have been shown to punch with more force than female boxers, and heavier boxers with more force than lighter boxers, although punch force relative to body mass has not been considered in these reports [6, 12, 70]. Further to this, the cross as well as hooks from the lead and rear hand have been reported as the most forceful punches, especially in comparison to the jab [76]. There is evidence to suggest that punch technique as well as the physical characteristics of a boxer (e.g. their muscular strength and power) are both positively related to the amount of force delivered in a punch [7, 77], however no studies have directly tested this hypothesis by measuring both punch force and punch kinematics. Moreover, only one study has examined the relationship between muscular strength and power and punch impact force, and many details regarding the specific muscular properties that may be associated with increased punch force remain unknown.

The components for success in amateur boxing competition under the TPMS are not well defined. Additionally, the technical and physical characteristics that are necessary to create high punch impact forces are also not clearly described, and the effect of fatigue on a boxer's performance under the TPMS and their capacity to punch with high force remains unknown. Hence, a better understanding of the actions indicative of successful boxing performance, and the specific muscular strength and power characteristics necessary to generate punch force are required to assist boxers and coaches to maximise physical, technical and tactical preparations. As such, future research should aim to identify technical and behavioural factors that are associated with success in amateur boxing under the TPMS as well as identify the upper- and lower-body muscular strength and power characteristics that are related to producing high punch impact forces. Furthermore, the effect of muscular fatigue on competition boxing performance and the ability to produce punch force should also be explicitly tested in future research.

CHAPTER 3.

Human behaviours associated with dominance in elite amateur boxing bouts: A comparison of winners and losers under the Ten Point Must-System

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3.1 Abstract

Humans commonly ascertain physical dominance through non-lethal fighting by participating in combat sports. However, the behaviours that achieve fight dominance are not fully understood. Amateur boxing competition, which is judged using the subjective “Ten Point Must-System”, provides insight into fight dominance behaviours. Notational analysis was performed on 26 elite male competitors in a national boxing championship. Behavioural (guard-drop time; movement style [stepping/bouncing time]; clinch-time; interaction-time) and technical (total punches; punches landed [%Hit]; air punches [%Air]; defence) measures were recorded. Participants reported effort required (0 - 100%) and perceived effect of fatigue on their own performance (5-point Likert scale) following bouts. Differences between winners and losers, and changes across the duration of the bout were examined. Winners punched more accurately than losers (greater %Hit [33% vs. 23%] and lower %Air [17% vs. 27%]) but total punches, defence and interaction-time were similar. From rounds 1 - 2, clinch-time and guard drops increased whilst bouncing decreased. Perceived effect of fatigue increased throughout the bout while perceived effort increased only from rounds 2 - 3. %Hit and movement index together in regression analysis correctly classified 85% of bout outcomes, indicating that judges (subjectively) chose winning (dominant) boxers according to punch accuracy and style, rather than assertiveness (more punches thrown). Boxers appear to use tactical strategies throughout the bout to pace their effort and minimise fatigue (increased guard drops, reduced bouncing), but these did not influence perceived dominance or bout outcome. These results show that judges use several performance indicators not including the total number of successful punches thrown to assess fight dominance and superiority between fighters. These results provide valuable information as to how experienced fight observers subjectively rate superiority and dominance during one-on-one human fighting.

3.2 Introduction

Fighting for dominance is a behaviour observed in many primates, including humans [78]. Dominating a rival in physical confrontation while peers observe has numerous social and physical advantages in the wild [33]; often a fight takes place in front of a crowd of peers, which helps the winner to consolidate their dominance within the group [34]. In modern human society, physical confrontation may be less common, however the instinct to assert dominance and promote hierarchical organisation is still entrenched [35, 79]. Combat sports provide an acceptable outlet for those desiring the challenges associated with physical confrontation and provide a vehicle for gaining insight into perceptions of dominance in humans.

In modern amateur boxing, male boxers compete in specified weight categories over three, 3-min rounds (each separated by 1-min of recovery) to determine a winner. Competitors aim to punch their opponent whilst avoiding their opponent's punches. Until 2013, winners were decided by judges counting the number of clean blows landed to the target area at the front of the torso (on or above the line of the belt) and the front and side of the head [80], in 2013 the judging system was changed to the "Ten Point Must-System" (TPMS). After each round, judges award the winning boxer 10 points and the losing boxer between 6 and 9 points depending on their perception of the closeness of the contest. At the end of the contest, each judge awards the winner based on which boxer has the most points. Under the TPMS there are four criteria with which the judges assess the contest: 1) the number of quality blows on the target area, 2) domination of the bout by technical and tactical superiority, 3) competitiveness, and 4) lack of infringement of the rules [80]. In contrast to the previous scoring system, the TPMS deliberately incorporates a greater subjective component. Key words in the judging criteria indicative of the role of subjectivity are 'superiority', 'dominance' and 'competitiveness'. In order to win, boxers must demonstrate superiority over their opponent across multiple criteria rather than simply landing more punches on the target area. In a recent study of the new rules, Davis and colleagues found that the accuracy of punches thrown, rather than the total number of punches landed, was higher in winners [3]. Such data suggest that subjective decisions regarding superiority, dominance and competitiveness are made using observational cues other than the total number of successful punches alone. The primary aim of this study therefore, was to determine which fight-related actions are more likely to be associated with winning under the TPMS through the examination of a wide range of technical, behavioural and perceptual variables during elite male amateur boxing bouts, with the assumption that this will provide insight into the cues used by humans (who regularly observe fights) to determine fight dominance.

The Cumulative Assessment Model of fighting strategies integrates the metabolic cost and the cost of physical damage to theorise the outcome of contests between animals [81]. This theory declares that when a contestant suffers more fatigue than its rival it shall either retreat from, or lose the contest [82], in both cases being less dominant. Given the strenuous nature of amateur boxing [1] fatigue may affect a boxer's ability to perform in the ring [24]. We hypothesised that experiencing fatigue, or the demonstration of behaviours which indicate potential fatigue, during a competitive bout would affect the boxer's behavioural and technical actions, which could in turn affect the judge's perception of who was the dominant boxer. Therefore a secondary aim of this study was to monitor changes in technical and behavioural variables over the three rounds of elite boxing bouts, with added context being contributed by the boxers' perceptions of effort and fatigue throughout, to determine if specific fatigue-related behaviours were associated with winners.

3.3 Methods

3.3.1 Human participants

Twenty-six amateur boxers (mean age ± [SD] 22.2 ± 2.6 years) who competed in the Elite Male under 64 kg, under 69 kg and under 75 kg weight divisions at the 2015 Australian Boxing Championships participated in this study. All participants gave written informed consent before taking part in the study and were made aware they could withdraw their data at any time. The study was approved by the Human Research Ethics Committee at Edith Cowan University and all procedures were performed in accordance with the Declaration of Helsinki.

3.3.2 Data capture procedures

Participants competed in a boxing bout consisting of three 3-min rounds scored using the TPMS. Only bouts that lasted the full fight duration were selected for analysis. Video footage was captured at 50 frames/second from a video camera (AVCHD NXCAM, Sony Corporation, Tokyo, Japan) positioned at the ringside such that the whole bodies of both boxers were captured in the frame. Notational analysis of one bout per participant, from the first or second rounds of the tournament, was included in analysis (no boxer was analysed in more than one bout). Data were collected from 19 bouts, nine where both boxers were analysed and eight where only one boxer was analysed (due to their opponent having already been analysed as part of a previous bout). Notational analysis for each participant consisted of reviewing video footage between three and four times at one-quarter speed to tag and label specific techniques and behavioural patterns using the coding software (SportsCode Elite software; SportsTec, Hudl, Sydney, NSW, Australia). An experienced analyst conferred with elite boxing coaches to develop all variables recorded during notational analysis (Table 3.1). All bouts were analysed by the same experienced analyst who conferred with elite boxing coaches throughout a piloting phase. Three participants were analysed twice to determine the analyst's intra-tester reliability (Pearson's $r = 0.98$). The same three bouts were analysed by a second analyst (who was similarly trained) to determine the inter-tester reliability (Pearson's $r = 0.97$) of the primary analyst. Only bouts analysed by the primary analyst were included in the statistical analysis. Perceptual variables were gathered via verbal surveys conducted within 30 min of the boxers leaving the ring after their bout. Boxers were asked "How much effort was required in round 1, 2, 3 and overall?" (recorded as a percentage) and "Do you think fatigue effected your performance in round 1, 2, 3 and overall" (recorded on a 5-point Likert scale). All perceptual ratings were collected by the same researcher.

3.3.3 Statistical analysis

Data were analysed using IBM SPSS Statistics (version 19) and all data are expressed as mean ± SD. A two-way multiple variable analysis of variance (MANOVA) with repeated measures was used to analyse groups of related variables (technical, behavioural, descriptor and perceptual) and interactions between rounds and groups. Alpha was set at $p < 0.05$. Where significant effects were observed, a Tukey's post-hoc test was used to identify where differences occurred. Cohen's *d* effect sizes (ES) and 95% confidence intervals (CI) of the differences were calculated. Effect size magnitudes were classified using the scale advocated by Rhea for trained athletes in which < 0.25, 0.25 - 0.5, 0.50 - 1.0 and > 1.0 were termed trivial, small, moderate and large, respectively [83]. Binomial logistic regression analyses were performed on selected variables that represent accuracy (%Hit), volition (total punches thrown) and general movement style (movement index expressed as bounce: step ratio) in three different models: 1) %Hit only, 2) %Hit plus movement index and 3) %Hit plus movement index and total punches thrown.

Table 3.1. Description of variables collected during notational analysis of amateur boxing.

Category	Variable	Unit	Description
Technical	Punches thrown	Number	Total number of punches thrown
	Hit	Number	A punch that hit the target area
	Miss	Number	A punch that made contact with the opponent outside the target area
	Air	Number	A punch that failed to make contact with the opponent
	%Hit	%	The number of hits expressed as a percentage of total punches thrown
	%Miss	%	The number of misses expressed as a percentage of total punches thrown
	%Air	%	The number of air punches expressed as a percentage of total punches thrown
	Defensive actions	Number	Number of all defensive techniques including arm, body and leg defences
Behavioural	Guard drop	Seconds	Active lowering of the gloves, or holding a guard noticeably lower than when the fight commenced
	Bounce time	Seconds	Time boxer spent with feet moving in an synchronised pattern
	Step time	Seconds	Time boxer spent with feet move in an alternating pattern
	Movement index	Ratio	Ratio of time spent bouncing to stepping
	Clinch time	Seconds	One or both boxers holding their opponent
	Interaction time	Seconds	Time spent interacting with the opponent (punching, defending etc.; excludes clinches)
Bout descriptor	Referee stoppage time	Seconds	Time between referee calling “stop” and resuming the bout, does not include break calls
	Total round time	Seconds	Time between start and end bells of each round
Perceptual	Effort rating	%	Rating of how much effort was required during each round as a percentage of maximum effort
	Fatigue rating	Rating 1-5	Rating on a 5-point Likert scale the extent to which boxers believed their performance was affected by fatigue in each round

3.4 Results

3.4.1 Comparison of winners and losers

Analysis showed a significant main effect ($p = 0.043$) of bout outcome (winners [n = 12] vs. losers [n = 14]) for technical variables (Table 3.2). Specifically, winners' %Hit was significantly higher than losers in all rounds and showed large effects in rounds 1 ($p < 0.001$; ES = 1.39; CI = 0.49 - 2.20) and 2 ($p = 0.007$; ES = 1.16; CI = 0.30 - 1.95) and moderate effects in round 3 ($p = 0.007$; ES = 0.87; CI = 0.04 - 1.65). %Air was significantly lower in winners than losers in round 2 ($p = 0.005$; ES = −1.08; CI = −1.87 - −0.23). Total punches thrown, total defensive actions, and %Miss were similar between winners and losers at each time point, with non-significant main effects being observed ($p = 0.780$, $p = 0.870$, $p = 0.240$, respectively).

Logistic regression models were significantly different from the null model. %Hit (χ^2 [1] = 10.685, $p < 0.001$) explained 45% of the variance (Nagelkerke R^2) and correctly classified 76.9% of winners and losers. When movement index was added to %Hit the model (χ^2 [2] = 12.414, $p = 0.002$) explained 50.7% of variance and correctly classified 84.6% of bout results. Finally, when total punches was added to %Hit and movement index (χ^2 [3] = 12.465, $p = 0.006$), 50.9% of variance was explained; however the prediction was slightly lower, correctly classifying only 80.8% of bout results.

There was no significant main effect ($p = 0.420$) between winners and losers for behavioural variables (Table 3.3). In some behavioural variables effect sizes indicated potential discrepancies between winners and losers but large confidence intervals made these outcomes unclear. Accordingly, moderate effect sizes for movement variables (movement index and step time and bounce time) suggested winners bounce more and step less than losers in all three rounds (movement index, round: 1 ES = −0.57; CI = −1.34 - 0.23; round 2: ES = −0.52; CI = −1.29 - 0.28; round 3: ES = −0.50; CI = −1.27 - 0.30; bounce time, round 1: ES = 0.68; CI = −0.13 - 1.45; step time, round: 1 ES = −0.69; CI = −1.46 - 0.12; round 3: ES = −0.59; CI = −1.36 - 0.21). Additionally moderate effect size (round: 1 ES = 0.62; CI = −0.19 - 1.39; round 2: ES = 0.63; CI = −0.18 - 1.40; round 3: ES = 0.53; CI = −0.27 - 1.29) suggests winners may drop their guard for longer durations in all three rounds compared to losers. There were no between-group effects for perceptual measures ($p = 0.390$; Table 3.3).

Table 3.2. Technical movements by round, for winners and losers of competitive boxing bouts.

		Round 1	Round 2	Round 3
Punches thrown	Winners	75.8 ± 23.4	78.0 ± 29.4	75.7 ± 20.3
	Losers	78.6 ± 25.0	78.6 ± 28.8	80.7 ± 30.2
	All boxers	77.3 ± 23.8	78.3 ± 28.5	78.4 ± 25.7
Hit	Winners	25.0 ± 10.5	26.3 ± 12.4	23.8 ± 6.2
	Losers	17.4 ± 8.2	19.9 ± 10.6	21.1 ± 9.3
	All boxers	20.9 ± 9.9	22.9 ± 11.7	22.4 ± 8.0
Miss	Winners	37.3 ± 14.3	40.8 ± 12.3	39.8 ± 12.6
	Losers	43.2 ± 16.2	43.4 ± 16.8	44.9 ± 19.4
	All boxers	40.5 ± 15.4	42.2 ± 14.7	42.6 ± 16.5
Air	Winners	13.6 ± 8.3	10.8 ± 7.9	12.1 ± 8.2
	Losers	18.0 ± 9.3	15.3 ± 6.5	14.6 ± 6.2
	All boxers	16.0 ± 9.0	13.2 ± 7.4	13.5 ± 7.2
% Hit	Winners	33.1 ± 9.4	33.1 ± 6.9	32.0 ± 6.7
	Losers	21.6 ± 7.2 *	24.4 ± 7.9 *	26.2 ± 6.6 *
	All boxers	27.0 ± 10.0	28.4 ± 8.5	28.9 ± 7.1
% Miss	Winners	49.2 ± 9.5	53.9 ± 7.2	52.8 ± 8.1
	Losers	54.6 ± 9.5	55.7 ± 8.3	54.6 ± 6.2
	All boxers	52.1 ± 8.6	54.9 ± 7.7	53.8 ± 7.0
% Air	Winners	17.7 ± 9.0	13.0 ± 6.1	15.2 ± 8.7
	Losers	23.8 ± 10.3	19.9 ± 6.5 *	19.1 ± 7.4
	All boxers	21.0 ± 10.1	16.7 ± 7.1	17.3 ± 8.1
Defensive actions	Winners	31.8 ± 11.9	31.3 ± 12.6	29.4 ± 15.2
	Losers	30.6 ± 13.3	29.9 ± 12.4	29.6 ± 11.3
	All boxers	31.2 ± 12.5	30.5 ± 12.3	29.5 ± 12.9

* = significantly different to winners at the same time point as determined by a two-way MANOVA with repeated measures; winners, n = 12; losers, n = 14; all boxers, n = 26.

3.4.2 Changes in technique, behaviour and perception over time

Within-subject analysis of all participants (n = 26) showed that technical outcome measures remained consistent over the three rounds (no within-subject main effect; Table 3.2). Analysis of behavioural variables showed a significant main effect (p = 0.001) over the three rounds of the contest (Table 3.3). Specifically, absolute bounce time decreased from rounds 1 - 2 (p < 0.001; ES = −0.42; CI = −0.63 - −0.22) and 1 - 3 (p < 0.001; ES = −0.46; CI = −0.71 - −0.22), and movement index increased from round 1 - 2 (p = 0.017; ES = 0.40; CI = 0.09 - 0.72). However, absolute step time did not change significantly and only small effect sizes were observed over the rounds. Guard drop time increased significantly from rounds 1 - 2 (p = 0.012; ES = 0.46; CI = 0.11 - 0.80) and 1 - 3 (p = 0.002; ES = 0.66; CI = 0.27 - 1.06). Clinch time increased significantly, with moderate effects from rounds 1 - 2 (p = 0.004; ES = 0.57; CI =

0.22 - 0.93) and 1 - 3 ($p < 0.001$; ES = 0.83; CI = 0.43 - 1.23). For perceptual measures, there was a significant within-subject main effect ($p < 0.001$), with effort ratings increasing significantly from rounds 1 - 3 ($p < 0.001$; ES = 0.80; CI = 0.50 - 1.10) and 2 - 3 ($p < 0.001$; ES = 0.62; CI = 0.33 - 0.91). Fatigue ratings increased significantly at each time point, with moderate effect sizes for rounds 1 - 2 ($p < 0.001$; ES = 0.74; CI = 0.41 - 1.08) and 2 - 3 ($p = 0.01$; ES = 0.69; CI = 0.20 - 1.19) and large effect sizes for rounds 1 - 3 ($p < 0.001$; ES = 1.44; CI = 0.74 - 2.13).

Table 3.3. Behavioural and perceptual measures and bout descriptors by round.

		Round 1	Round 2	Round 3
Guard drop (s)	Winners	28.8 ± 16.0	37.2 ± 22.8	39.5 ± 21.2
	Losers	20.0 ± 12.7	25.7 ± 13.2	29.5 ± 16.6
	All boxers	24.1 ± 14.7	31.0 ± 18.8 *	34.1 ± 19.2 *
Step time (s)	Winners	56.0 ± 19.7	65.5 ± 23.8	56.0 ± 22.8
	Losers	70.8 ± 22.8	72.1 ± 28.9	69.1 ± 21.5
	All boxers	64.0 ± 22.3	69.0 ± 26.4	63.0 ± 22.7
Bounce time (s)	Winners	66.9 ± 25.6	50.9 ± 27.6	49.4 ± 25.9
	Losers	49.0 ± 26.8	40.5 ± 27.9	39.7 ± 25.8
	All boxers	57.3 ± 27.3	45.3 ± 27.7 *	44.2 ± 25.8 *
Movement index	Winners	1.27 ± 1.46	1.92 ± 1.57	1.71 ± 1.47
	Losers	2.20 ± 1.74	2.92 ± 2.18	2.63 ± 2.08
	All boxers	1.77 ± 1.65	2.46 ± 1.95 *	2.20 ± 1.85
Effort rating (%)	Winners	65.8 ± 16.1	75.2 ± 11.6	85.7 ± 9.2
	Losers	79.2 ± 18.8	77.6 ± 22.1	90.5 ± 12.2
	All boxers	73.0 ± 18.5	76.5 ± 17.7	88.3 ± 11.0 * ǂ
Fatigue rating (1-5)	Winners	1.58 ± 0.67	2.08 ± 0.90	2.58 ± 1.56
	Losers	1.64 ± 0.84	2.29 ± 1.20	2.86 ± 1.66
	All boxers	1.62 ± 0.75	2.19 ± 1.06 *	2.73 ± 1.59 * ǂ
Referee stoppage time (s)	All boxers	8.9 ± 9.0	18.5 ± 14.1 *	24.9 ± 16.8 * ǂ
Total round time (s)	All boxers	180.2 ± 1.5	185.2 ± 10.0 *	185.3 ± 9 .0 *
Interaction time (s)	All boxers	85.7 ± 15.8	93.2 ± 20.9	97.0 ± 17.7 *
Clinch time (s)	All boxers	11.1 ± 10.0	17.1 ± 9.3 *	19.8 ± 11.7 *

* = significantly different ($p < 0.05$) to round 1; ǂ = significantly different to round 2 as determined by a two-way MANOVA with repeated measures; winners, n = 12; losers, n = 14; all boxers, n = 26.

3.4.3 Interaction effects

There were no significant interaction effects between rounds and bout outcome (winners and losers) for the groups of variables analysed. Round-by-bout outcome interactions for technical, behavioural and perceptual variables were associated with p values of 0.620, 0.648 and 0.459, respectively.

3.5 Discussion

The recent change to incorporate subjective judging criteria into amateur boxing challenges boxers to convince judges of fighting superiority and dominance. This provides a unique opportunity to study humans fighting for viewer-perceived dominance. The circumstance somewhat resembles fighting behaviour in humans and other primates in the animal kingdom and may provide insight into the cues used by humans to determine fight dominance (at least of experienced judges, who regularly observe fights). The results showed that winners had greater punch accuracy than losers, illustrated by a greater percentage of hits and lower percentages of air swings (Figure 3.1), but did not throw more punches in total. Thus, punch accuracy, rather than the total number of punches thrown, appears to be perceived as a key indication of dominance in well trained boxers. This finding is consistent with Davis and colleagues [3], who reported accuracy to be more favourable in winners than losers in a sample of elite male boxers competing at an international tournament. Interestingly, and also consistent with the findings of Davis and colleagues [3], neither the total number of punches thrown nor the absolute number of punches that were classified as hits, misses or air swings significantly differed between winners and losers. This finding suggests that having a high success rate is more favourable for victory than throwing and landing more punches than the opponent in total. Thus, the characteristics of winning boxers differs under the TPMS and previous 'punch count' system (where total number of successful punches characterised the winner [74]), and indicates that the judges' perceptions of 'superiority', 'dominance' and 'competitiveness' are formed by more complex observations than the total number of successful punches thrown by a fighter.

Each instance in which a boxer hits the other is a complex encounter, but might be viewed as a function of both boxers' skill levels. Hristovski and colleagues [84] demonstrated that boxers decided which punch to throw based on 'reachability', a skill that relies on visual cues and perceptions. Furthermore, Jackson and colleagues [85] reported that expertise level was related to the ability to use and detect deceptive actions in the collision sport of Rugby Union. This observation may be pertinent in boxing given the tactical use of feigning by combatants. It is possible that winners have developed these skills to a greater extent than losers, which allowed them to overcome the opponents' defence systems (with the use of superior deception or feigning) to land the punches and avoid throwing air-swinging punches; however this hypothesis remains to be explicitly tested in subsequent studies. Judges' perceptions of a boxer punching with efficiency (hitting often and air swinging infrequently) seem to be more positive than for boxers throwing a lot of punches in total but with less efficiency (hitting and air swinging at similar rates). Indeed it is possible that as long as the judges believe the boxer looks good they may win the bout [3].

To explore the possibility that actions and behaviours other than punching accuracy could influence judge perception of dominance we selected and analysed behavioural variables such as dropping of the guard and style of movement around the ring (i.e. bouncing or stepping). This analysis revealed no statistical differences between winners and losers for the behaviours we monitored. When studying boxers who were fighting under the previous (punch count) system, when judge perception of how the boxers moved should not have influenced the bout outcome, winners were observed to display a greater number of vertical hip movements (VHM; defined as any visually identifiable vertical activity of the pelvis during stand and steps, which has been mainly attributed to bouncing) than losers [27, 74]. This result suggests that movement style might have had some influence on bout outcome. However, when studying boxers under the new TPMS, the same research group found no differences in VHM between winners and losers or changes throughout the bout [3]. In contrast, in the present study a tendency for winners to have a more vertical than translational movement style (i.e. more bouncing and less stepping) compared to winners was observed, with moderate effect sizes being calculated. Also, the logistic regression analyses revealed that the model with the best predictive outcome included information describing punch accuracy as well as movement styles; 84.6% of bout outcomes were correctly classified when the variables '%Hit' and 'movement index' were included. Whether this is due to the movement style offering a technical advantage or whether it provides an aesthetic advantage and consequently contributes to a positive judge perception cannot be determined from the present data and should be investigated in future research (through interview of the judges, for example). However this outcome reinforces the hypothesis that judge perception might be influenced by more than just information relating to punching accuracy. The notion that movement style might influence perception of performance is not unique to boxing. Cormack and colleagues showed a fatigue-induced reduction in vertical acceleration during high speed running, which was associated with reduced coaches' perception of the players' performances in Australian Rules football players, irrespective of the players' running rates (metres per min and high-speed running metres per min) during match play [15]. Such findings, in conjunction with the current results, indicate that humans may use general movement cues to make decisions regarding performance ability and the superiority of one athlete over another.

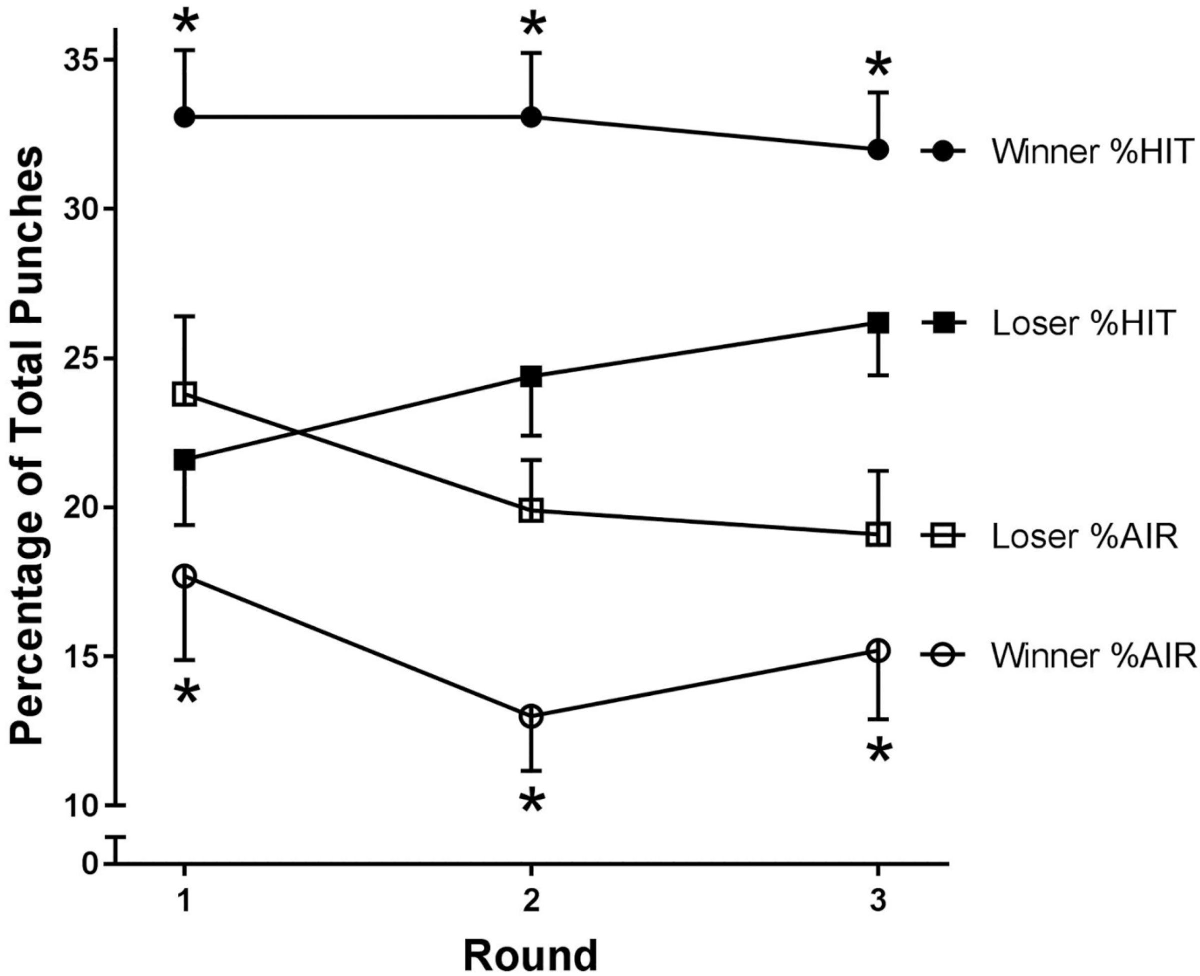

Figure 3.1. %Hit and %Air in winning and losing boxers over three rounds of tournament boxing. Winners are more accurate than losers, shown by significantly higher %Hit and significantly lower %Air compared to losers. Values expressed as mean ± SE; * = significantly (p < 0.05) different from losers as determined by a two-way MANOVA with repeated measures.

As boxing is a physically demanding sport (e.g. work: rest ratios as high as 19.3:1[3]), fatigue can be linked to poor performance or behaviour change [86], and that fatigue may be the cause of defeat or the decision to flee in combative situations in animals [82]. We therefore also analysed changes in technical and behavioural variables over the duration of the match and included additional perceptual variables. The number of punches and defensive techniques used did not change throughout the bout. From this finding, one might conclude that the competition demands induced minimal fatigue. However, it is common for movement patterns to vary in order to maintain performance demands, a concept commonly referred to as pacing [86, 87] and defined as the regulation of exercise intensity with the intention to avoid early exhaustion while achieving a desired outcome [88]. The inclusion of perceptual data in the current study offers novel and unique insights that help us to better understand behavioural change during a boxing bout and provides information pertinent to pacing strategies, which might influence judge perception of dominance. Behavioural and perceptual variables, unlike technical variables, clearly fluctuated over the duration of the bout. Specifically, movement style, guard drops and clinching all changed from rounds 1 - 2 but not 2 - 3. The perceptual variables, on the other hand, followed a different pattern. Boxers' perception of effort increased significantly only from rounds 2 - 3 while their perceived effect of the fatigue on their performance increased in all rounds (from rounds 1 - 2 and 2 - 3; Figure 3.2). This decoupling of fatigue rating, perceived effort and behaviour suggests that pacing strategies may be used at various stages of a boxing bout to mitigate the effect of fatigue. Furthermore, while increasing significantly, the extent to which boxers believe that their performance was affected by fatigue only reached moderate levels at the conclusion of the bout, which may have been because boxers effectively pace their efforts throughout the bout. Moreover, knowledge of the exercise end point might have also caused the late increase in effort required [89]; similar to the end spurt seen in most pacing profiles [90]. These findings indicate that movement patterns and behaviour such as guard dropping and clinching could be altered as a pacing strategy to avoid fatigue over the duration of an amateur boxing bout.

The behavioural concepts measured have been referred to in existing literature, although the pertinence to fatigue and pacing as not been explored before. Increases in guard drop are consistent with previous literature [22, 27, 74] and, if not specifically used for tactical purposes (e.g. to change the behaviours seen by the opponent), could be considered to be behaviours adopted to gain brief periods of rest for the smaller muscle groups of the upper body. Allen and Westerblad [91] suggested that a rest as short as a few seconds can be sufficient for the partial, rapid recovery of working muscle. The increase in clinching time (round 1 - 2) in all boxers might be a preferable behaviour in the later stages of a bout (when fatigue might become apparent) in order to avoid the opposing boxers optimal striking zone (i.e. clinching is a safety mechanism). However, clinching could also be used as a means to draw a stoppage and gain a brief rest. Collectively, altered movement style, guard and clinching behaviours could be used by boxers to moderate their exertion over the bout to maintain the number of punches and defensive actions used. Viewed in conjunction with these behaviour changes, the inclusion of perceptual data in the current study allows us to expand on this idea by providing extra information pertinent to pacing strategies.

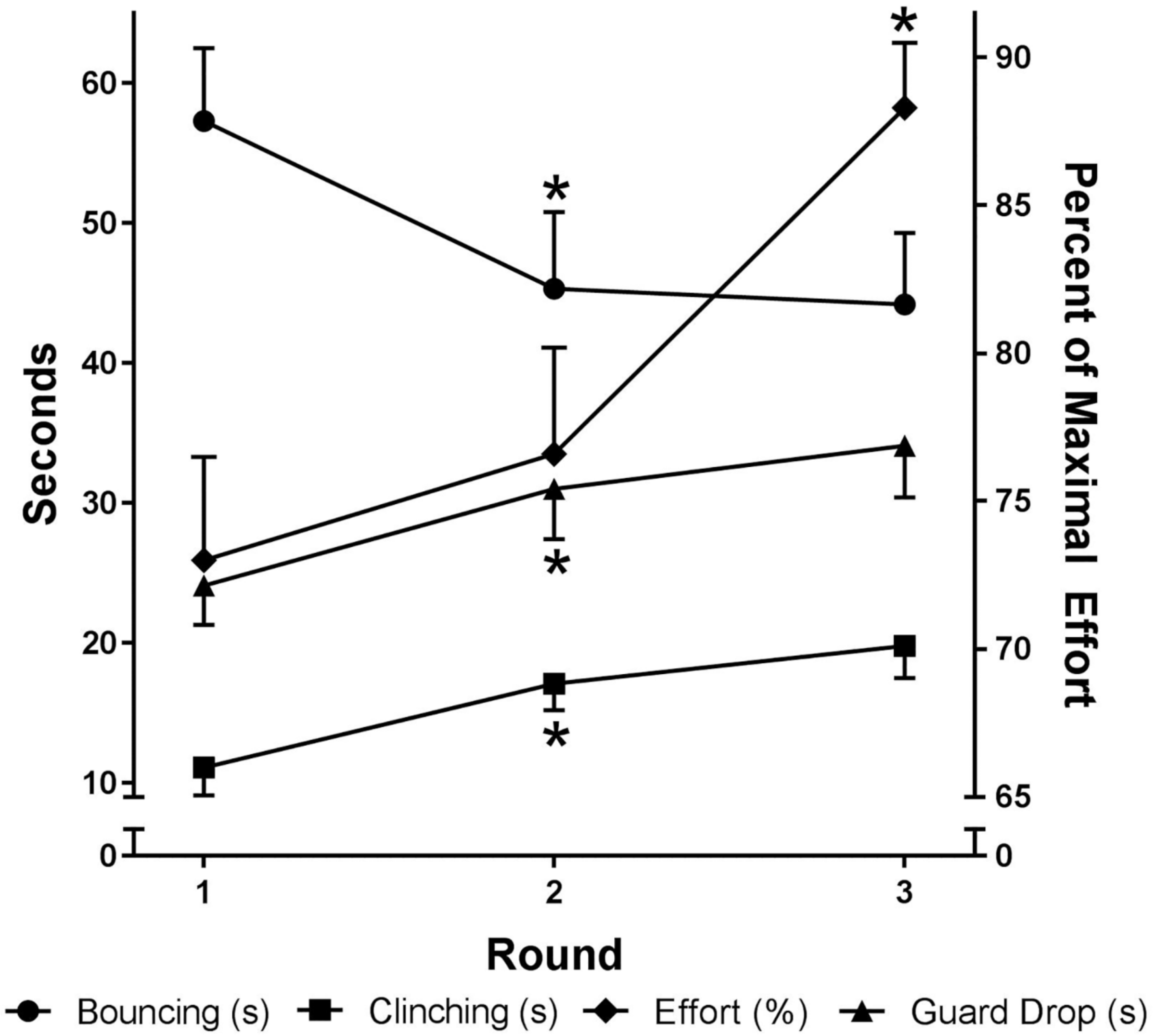

Figure 3.2. Behaviour (clinch time, guard drop time and bounce time) and perceived effort over three rounds of tournament boxing. Behaviour changes significantly from round 1 - 2 while perception of fatigue only from round 2 - 3, which may indicate pacing strategies have been used by boxers. Values expressed as mean ± SE; * = significantly ($p < 0.05$) different the previous round losers as determined by a two-way MANOVA with repeated measures.

As highlighted previously there are clear behavioural and perceptual changes in all boxers throughout the bout and clear differences in punch accuracy between winners and losers. We hypothesised that experiencing fatigue, or the demonstration of behaviours which indicate potential fatigue, could affect the judge's perception of who was the dominant boxer. In that case one might expect the behavioural changes over the course of the bout to become more pronounced in winners rather than losers. However, in the present study there were no significant interaction effects between time and the outcome of the bout. This indicated that winners were consistently more accurate than losers, but that behaviour change followed the same patterns in all boxers regardless of winning or losing the bout. Our findings are consistent with previous literature in that punch accuracy is the most important factor to ensure victory, although we also acknowledge that movement style may have some effect on the judges' perceptions or have a technical advantage for boxers. However to be successful in a boxing bout these characteristics must hold true over the duration of the bout.

3.6 Conclusion

In conclusion, under the current subjective TPMS scoring system in amateur boxing, punch accuracy appears to be more important than the total number of punches thrown as winners had greater punch accuracy than losers (greater percentage of hits and lower percentages of air swings) but total punches thrown had no detectable effect on bout outcome. It is possible that winners have superior skill sets and were able to overcome their opponent's defence system to land accurate punches, and that this was more important to 'subjective dominance' than overall assertiveness or volition (i.e. total punches thrown). Logistic regression analysis indicated that high punch hit percentage in conjunction with a vertical movement style was perceived by judges to indicate superiority. These data suggest that judges may not only take note of the punches that hit the opponent, but also use general movement patterns such as how the boxer moves around the ring, to decide which fighter is superior to the other. It is interesting that although boxers appeared to pace their effort to minimise the effects of fatigue by intermittently dropping their guard and using a translational movement style, there was no clear interaction between how these general movement patterns and behaviours change and the outcome of the bout. Regardless of win or loss, our analysis of boxers' behaviours showed clear changes across the duration of the bout and indicated that winning and losing boxers adopt similar pacing strategies. While fatigue and pacing may be considered in the assessment of fighting dominance, it appears that in this case all fighters (winners and losers) are affected similarly throughout the bout and the changes observed have no effect the judge's perception of who was the dominant fighter.

CHAPTER 4.

A damaging punch: Assessment and application of a method to quantify punch performance

Dunn, E.C., Humberstone, C.E., Iredale, K.F. & Blazevich, A.J. A damaging punch: Assessment and application of a method to quantify punch performance. *Translational Sports Medicine, 2019;00:1–7*

4.1 Abstract

Measurement of human punching performance in a reliable, quantitative manner is relevant to combat sport, military, assault investigation and concussion research contexts. A punching protocol (3MPT) was developed based on the performance demands of amateur boxing, and evaluated on a custom-built punch integrator (PI). PI mechanical reliability and accuracy were assessed by calculating the typical error (TE) and coefficient of variation (CV) for a range of known masses, and a within-subject, repeated-measures design was used to assess the test-retest reliability of the 3MPT. Fifteen male boxers (17.5 ± 0.5 years; 177.5 ± 9.5 cm; 73.0 ± 14.0 kg) were familiarised and then completed two 3MPT trials 90 min apart on two separate days (total of 4 tests). Peak punch force (N), relative peak force ($N \cdot kg^{-1}$), impulse to peak force (N·s), time to 10%, 50% and 90% of peak force (ms), time from 50% - 90% of peak force (ms), time to 200 N and 500 N (ms), and force at 5 ms and 10 ms (N) were compared between tests using a linear mixed model. Smallest worthwhile change (SWC) was also computed. PI mechanical data had excellent reliability and accuracy (CV < 0.1%). TE and SWC comparisons revealed that 3MPT can detect moderate and large changes in performance, however within-day reliability improved from day one (3.1 - 13.8%) to day two (2.3 - 5.1%) indicating a possible learning effect. Likewise, differences between test one and two were greater on day one than two. Numerous punch-related variables can be accurately and reliably measured using the 3MPT but repeat-trial familiarisation is suggested to reduce between-test variability.

4.2 Introduction

A single powerful punch can inflict devastating physical damage, ending a fist fight by knockout. Alternatively, effective and powerful punches thrown continually and consistently throughout a fight in both sanctioned (combat sport) and non-sanctioned bouts, can exert dominance and attain success [61]. Measurement of the force characteristics of various punch techniques is relevant for combat sports, forensic investigations of assault, military combat and concussion research.

Characteristics of forceful punches have been examined in single blows [12, 70] and during combination punches [65] in controlled laboratory conditions. Researchers examining punch force or technique (kinematics) have often used indirect methods of measurement, e.g. three-dimensional motion capture [65, 68] and water-filled punching bags fitted with pressure sensors [6]. However, Smith et al. [7] measured punch forces directly using a tri-axial dynamometer containing a piezoelectric transducer and were able to detect small differences in punch forces of elite, intermediate, and novice boxers. While peak punch force is undoubtedly an important factor in a damaging punch, head acceleration is the most damaging factor causing concussion [92]. Therefore measuring both force and other properties of punch impact (i.e. force, impulse, rate of force development; RFD) during punches is important, however a measurement tool that assesses numerous variables pertaining to punch performance has not previously been reported upon.

The aims of this study were to assess the mechanical accuracy and reliability of a punch measurement apparatus (the punch integrator; PI), and then to assess the reliability of a boxing-specific punch test. Analysis of punch dynamics delivered by an expert, such as a well-trained boxer, can be valuable in understanding human striking in broader contexts.

4.3 Methods

4.3.1 Participants

Fifteen highly-trained male amateur boxers (age, 17.5 ± 0.5 years; height, 177.5 ± 9.5 cm; body mass, 73.0 ± 14.0 kg) volunteered for the study. Boxers were ranked first or second in Australia for their age and weight categories. All participants gave written informed consent before taking part in this study and were made aware they could withdraw their data at any time. A parent or guardian provided informed consent for participants under 18 years. The study was approved by Edith Cowan University Human Research Ethics Committee (ID: 12233) and all procedures were performed in accordance with the Declaration of Helsinki.

4.3.2 Protocol design and description

The 3-min punch test (3MPT) was developed based on previously reported work rates and punch frequencies [22, 93] in amateur boxing competition. El-Ashker [24] and Davis and colleagues [3, 22] report straight punches (jabs and crosses) to be the most prevalent punches in competition boxing, followed by hooks. Typical work rate for elite boxers under current AIBA competition rules [2] ranges from 71 to 109 offensive and defensive actions per 3-min round of boxing (approximately 0.4 to 0.6 actions per second [3, 93]), although work rates as high as 1.9 actions per second have been reported when including locomotive actions (i.e. bouncing around the boxing ring) and clinching [3]. As such, the 3MPT contains predominantly straight punches with additional hooks to reflect the specific punch types thrown in a bout, and the work rate was 126 actions per round (0.7 actions per second). The increased punching load was determined (through pilot testing) to be practical for the time period of the test, and aimed to reflect the total work load of one round of boxing with punches rather than with variables that are not easily controlled or quantified (i.e. bouncing, clinching and defending without an opponent).

The 3MPT involved six repeats of 30-s cycles of activity (Figure 4.1). Each cycle consisted of five punching combinations triggered by a light and audible beep every 5 s followed by a 5-s recovery. The test began with boxers facing the PI at a self-selected distance ready to strike with their preferred foot forward. Three different punching combinations were performed within cycles: 1) straight-arm punches (jab, cross, jab, cross, cross), 2) lead-hand hooks (3 lead-hand hooks), and 3) rear-hand hooks (3 rear-hand hooks). Boxers moved into a self-selected position maintaining their natural stance on the appropriate side of the PI to execute lead- and rear-hand hooks.

4.3.3 Procedures

4.3.3.1 Human performance trials

A within-subject, repeated-measures study design was used to assess test-retest reliability. Participants completed a standardised boxing-specific warm-up including 5 min of aerobic activity (steady state rowing), dynamic muscle stretching and bag punching at progressively increasing intensities (50%, 75%, 90%, 100% of maximal effort), before completing the 3MPT. Participants were familiarised with the 3MPT on the first day and completed two tests separated by 90 min on the two subsequent days. Time of day and laboratory conditions were consistent (23.2 ± 0.6 °C, 41 ± 1.8% relative humidity, 131.2 ± 0.3 kPa) for all tests.

During the 5-s rest period at the end of each cycle, boxers were given standardised feedback relating to time remaining in the test. Boxers were told, “you are half way”, “you have one minute to go”, and “this is the last cycle” after the 3rd, 4th and 5th cycle respectively. No performance feedback was given during or after the trials.

Punch force was measured using the wall-mounted S-beam load cell (KAC-E, Angewandte System Technik Gruppe, Germany) in series with the punch pad that was 270 mm thick, and adjusted to shoulder-height for each participant (Figure 4.2). The load cell sampled continuously at 2000 Hz throughout the 3MPT. Heart rate (HR) was measured with a Polar chest-strap (Polar RS800, Kempele, Finland). Rating of Perceived Exertion (RPE; 6 - 20 a.u.; Borg [94] and blood lactate concentration [La^-] (Lactate Pro II, Arkray, Japan) were measured immediately after completion of the 3MPT.

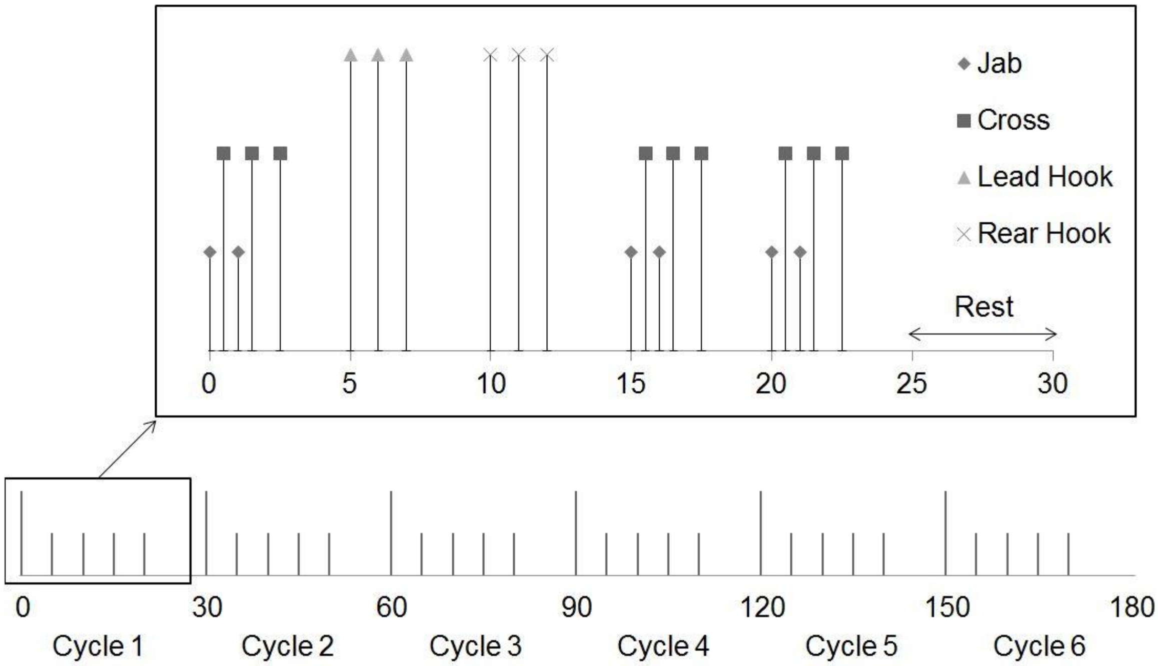

Figure 4.1. Schematic representation of the 3-min punch test (3MPT). The test consists of repeated 30-s cycles. Each cycle contains 5 punch combinations that include jabs, crosses, lead-hand hooks, rear-hand hooks, and a brief rest period.

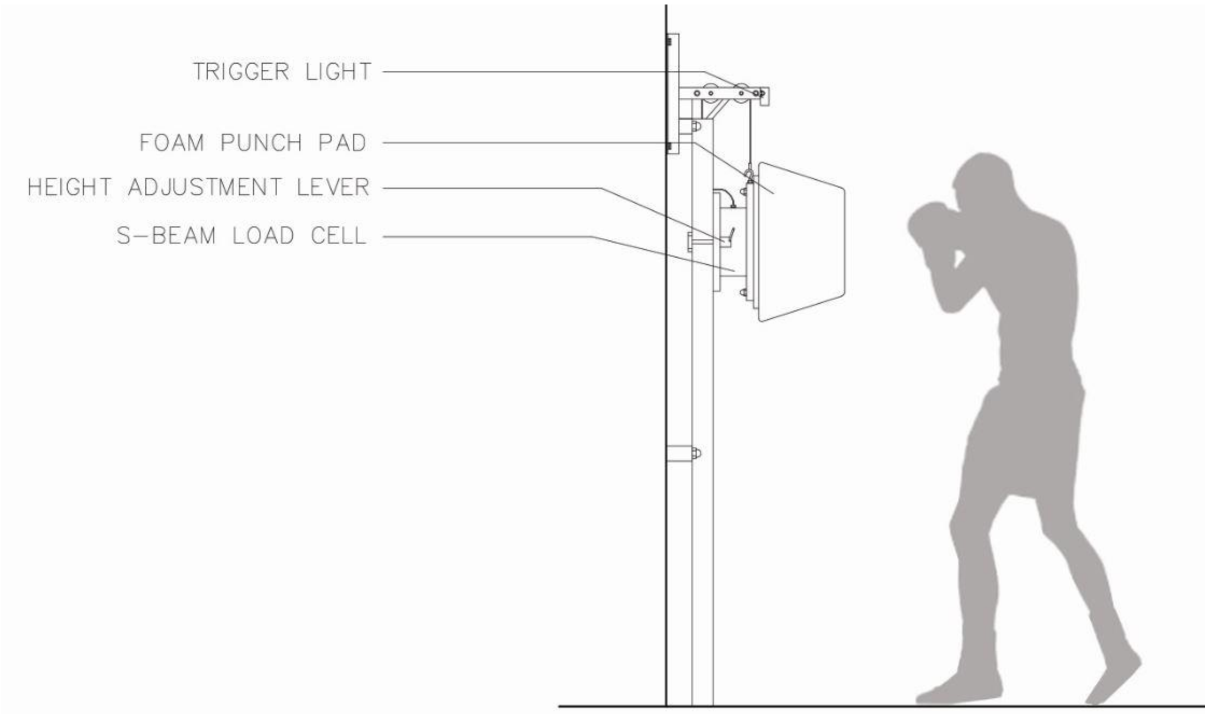

Figure 4.2. Diagram of the punch integrator setup and key components.

4.3.3.2 Mechanical reliability and accuracy trials

Mechanical evaluation of the PI was completed over two consecutive days to determine measurement accuracy and reliability (within-test, within-day and between-day). The S-beam load cell was assessed for linearity, reliability and drift. The load cell was placed on a stable and solid surface for assessment. Data were collected by software at a 2000 Hz analogue-digital frequency. Known loads were placed on the load cell incrementally up to 305.1 kg and left for 5 min before being incrementally unloaded. On day one the load cell was loaded twice, 90 min apart, and on day two it was loaded once, 24 hours after the first test on day one.

4.3.4 Data analyses

Customised software was used to identify punches in the force data then compute the necessary variables. The first 2 s of each trial, before any punches were thrown, was used as an offset window; data for each trial were normalised according to the offset window average. A punch was identified when 10 consecutive samples read above 10 times the standard deviation of the offset window. Punches were rejected if peak force was below 500 N. Once a punch was identified, the beginning and end of the punch were identified by an algorithm as the first and last positive values surrounding the peak force (N; Figure 4.3). Subsequently a 7^{th} order polynomial was fitted from punch onset to peak force, and another from peak force to the end of the punch. If the punch trace contained noise such that the residual between the polynomial and raw curve was greater than 1%, the punch was excluded from analysis. Impulse from punch onset to peak force (force × time; impulse; N·s) was calculated by integrating the first polynomial equation. The following variables were subsequently extracted from the smoothed trace: time to 10%, 50% and 90% of peak force ($t_{F10\%}$, $t_{F50\%}$ and $t_{F90\%}$, respectively; ms), time from 50% to 90% of peak force ($t_{F50\text{-}90\%}$; ms) time to 200 N and 500 N (t_{200N} and t_{500N}, respectively; ms), force at 5 ms and 10 ms (F_{5ms} and F_{10ms}, respectively; N). Relative punch force ($N{\cdot}kg^{-1}$) was calculated for each participant (punch force ÷ body mass).

To determine test reliability, all 3MPT trials were analysed with a linear mixed-model with two levels (day, test and day-by-test interactions). Post-hoc analyses were conducted where significant differences were detected. Alpha was set at $p < 0.05$. Typical error (TE), coefficient of variation (CV) and interclass correlation coefficient ($ICC_{3,1}$; two-way mixed, single measure; [95]) were calculated between test one and test two for both test days [96]. Smallest worthwhile change (SWC; based on between-subject SD; [97]) was calculated for small ($SWC_{0.2}$), moderate ($SWC_{0.6}$) and large ($SWC_{1.2}$) effect sizes and compared to TE scores [98]. ICC and SWC were calculated for change scores (test two - test one) on days one and two. Relationships between variables were assessed by calculating Pearson's correlation coefficients (r). Additionally, correlations between peak punch force and $t_{F50\%}$, t_{500N}, F_{5ms}, $t_{F50\text{-}90\%}$, and impulse were calculated using methods described by Bland and Altman [99] to establish if the strength of correlations differed. In these analyses every punch extracted from the participants' 3MPT was included (n = 6619).

To assess reliability of the mechanical loading trials, TE and CV for force measured at each increment was calculated. Typical error and CV were calculated between trial one and trial two on day one (within-day) and both trial one of day one and day two (between-day). Each trial was compared to theoretical calculations for known masses applied to the load cell by calculating correlations (Spearman's Rho [r_s], as data were non-parametric), and ICC. Theoretical values were calculated using Newton's second Law (Force = mass × acceleration). A one-way repeated measures analysis of variance (ANOVA) including all trials was used to check for significant statistical differences; alpha was set to $p < 0.05$.

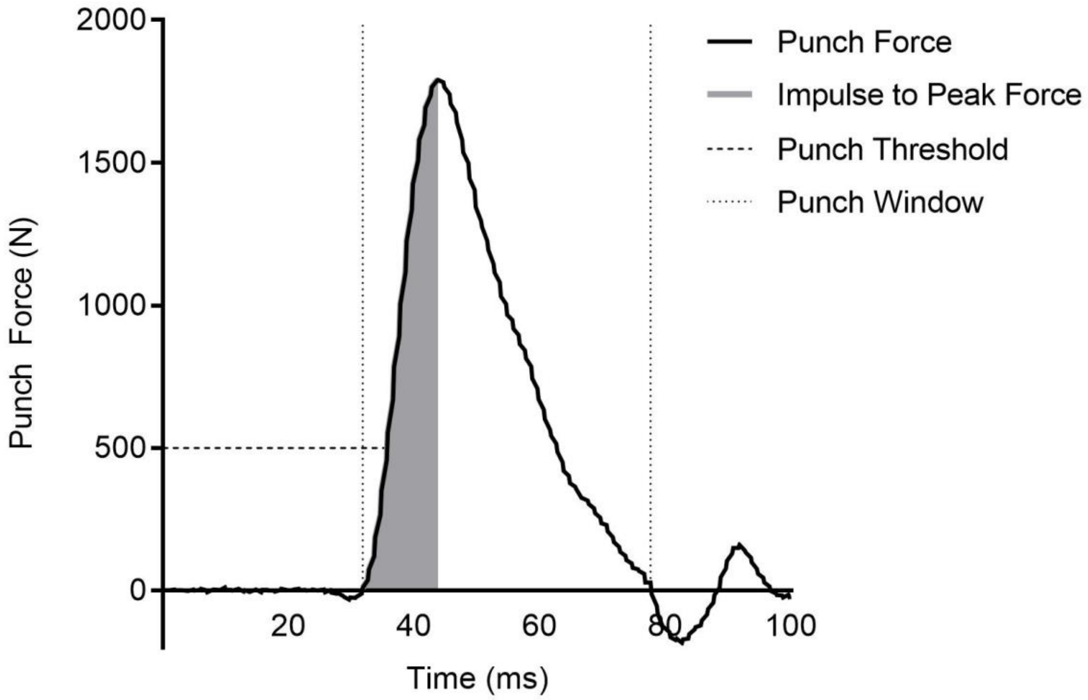

Figure 4.3. Example of raw punch data of a cross delivered during the 3MPT.

4.4 Results

4.4.1 Human performance trials

4.4.1.1 Within-day reliability

Several variables changed significantly from test one to test two on the first day of testing (Table 4.1), including decreases in overall peak force (p = 0.003), relative force (p = 0.003), impulse (p = 0.004), F_{5ms} (p = 0.008), F_{10ms} (p = 0.001), cross peak force (p = 0.015), relative force (p = 0.016), impulse (p = 0.002) and F_{10ms} (p = 0.020), lead- and rear-hand hook peak force (p = 0.006 and p = 0.005, respectively), relative force (p = 0.004 and p = 0.005), F_{5ms} (p < 0.001 and p = 0.026), and rear-hand hook t_{500N} (p = 0.043) and F_{10ms} (p = 0.013). Blood lactate concentration was also significantly lower in test two compared to test one (p = 0.005). On day two of testing t_{500N} (p = 0.042), F_{5ms} (p = 0.044) and F_{10ms} (p = 0.050) for rear-hand hook differed significantly between tests. Physiological data including peak HR, average HR, RPE and [La^-] are also reported in Table 4.1.

4.4.1.2 Between-day reliability

Variables that were significantly different in test one of each day (i.e. test one verses test three; see Table 4.1) included: cross F_{10ms} (p = 0.014), lead-hand hook F_{5ms} (p < 0.001), rear-hand hook t_{500N} (p < 0.001), F_{5ms} (p < 0.001) and F_{10ms} (p = 0.043), overall t_{500N} (p = 0.009), F_{5ms} (p = 0.010) and F_{10ms} (p = 0.031). Blood lactate concentration was also significantly lower (p = 0.005). There were significant interaction effects (time × day) for jab peak force and relative force along with lead-hand hook F_{5ms} and F_{10ms}. However, for all variables reliability of change scores for days one and two was poor to fair (according to ICC; Table 4.2).

TE and CV on day two were similar to or lower than day one for most variables (Table 4.3 and Table 4.4), except for jab $t_{F10\%}$, t_{200N} and t_{500N}, cross F_{5ms} and F_{10ms}, and rear-hand hook $t_{F10\%}$. TE was greater than $SWC_{0.2}$ but smaller than $SWC_{0.6}$ for most variables except overall relative force, impulse and $t_{F10\%}$, cross $t_{F10\%}$ and rear-hand hook peak force, relative force, impulse, and F_{10ms} on day one; and lead-hand hook impulse on day two (Table 4.2) which had TE scores that fell between moderate ($SWC_{0.6}$) and large ($SWC_{1.2}$).

Correlations for overall variables revealed strong and significant (p < 0.001) relationships between peak force and both impulse (r = 0.929 CI = 0.892 - 0.953) and F_{10ms} (r = 0.888, CI = 0.832 - 0.926). Strong correlations were found between $t_{F10\%}$ and $t_{F50\%}$ (r = 0.868; CI = 0.803 - 0.913; p < 0.001), $t_{F90\%}$ (r = 0.836; CI = 0.757 - 0.899; p < 0.001) and t_{200N} (r = 0.801; CI = 0.711 - 0.868; p < 0.001). Similarly, $t_{F50\%}$ and $t_{F90\%}$ were highly correlated (r = 0.965; CI = 0.946 - 0.977; p < 0.001), as were t_{200N} and t_{500N} (r = 0.957; CI = 0.934 - 0.972; p < 0.001). These trends were similar in each punch type, with correlations ranging 0.670 - 0.980 for jab, 0.490 - 0.973 for cross, 0.470 - 0.985 for lead-hand hook and 0.545 - 0.986 for rear-hand hook. Variables correlated with peak force are compared in Table 4.5.

Table 4.1. Punch impact force, punch RFD and physiological responses to the 3MPT over two days of repeat testing.

		Day 1		Day 2		Mean change day 1	Mean change day 2
		Test 1	Test 2	Test 3	Test 4		
Jab	Peak force (N)	871 ± 197	804 ± 175	841 ± 192	850 ± 194	-67 ± 115	10 ± 53 ǂ
	Relative force ($N\cdot kg^{-1}$)	12.0 ± 1.9	11.1 ± 1.8	11.6 ± 1.6	11.7 ± 1.5	-0.9 ± 1.5	0.1 ± 0.7 ǂ
	Impulse (N·s)	6.9 ± 1.8	6.2 ± 1.6	6.9 ± 1.7	6.9 ± 1.6	-0.6 ± 1.2	0.0 ± 0.6
	$t_{F10\%}$ (ms)	3.2 ± 1.3	2.9 ± 1.2	3.3 ± 1.4	3.2 ± 1.3	-0.2 ± 0.5	-0.1 ± 0.5
	$t_{F50\%}$ (ms)	7.7 ± 1.7	7.5 ± 1.7	8.0 ± 1.8	8.1 ± 1.8	-0.2 ± 0.8	0.1 ± 0.7
	$t_{F90\%}$ (ms)	12.5 ± 2.0	12.3 ± 2.1	12.9 ± 2.0	13.1 ± 2.0	-0.2 ± 0.8	0.1 ± 0.9
	$t_{F50\text{-}90\%}$ (ms)	4.7 ± 0.8	4.8 ± 0.6	5.0 ± 0.4	4.9 ± 0.5	0.1 ± 0.7	0.0 ± 0.4
	t_{200N} (ms)	5.0 ± 1.6	5.0 ± 1.3	5.3 ± 1.5	5.2 ± 1.5	-0.1 ± 0.6	-0.1 ± 0.6
	t_{500N} (ms)	8.6 ± 2.3	8.7 ± 2.1	9.1 ± 2.3	9.3 ± 2.2	0.2 ± 0.8	0.3 ± 1.2
	F_{5ms} (N)	261 ± 105	244 ± 83	237 ± 77	236 ± 78	-17 ± 36	-1 ± 28
	F_{10ms} (N)	634 ± 213	580 ± 164	579 ± 175	572 ± 172	-53 ± 100	-7 ± 52
Cross	Peak force (N)	1883 ± 318	1790 ± 348 *	1830 ± 354	1769 ± 350	-92 ± 113	-61 ± 111
	Relative force ($N\cdot kg^{-1}$)	26.1 ± 2.9	24.8 ± 2.9 *	25.3 ± 3.1	24.6 ± 3.9	-1.4 ± 1.7	-0.7 ± 1.6
	Impulse (N·s)	14.4 ± 2.5	13.1 ± 2.9 *	14.6 ± 2.7	14.1 ± 2.7	-1.3 ± 2.2	-0.4 ± 1.0
	$t_{F10\%}$ (ms)	2.7 ± 0.4	2.7 ± 0.4	2.8 ± 0.4	2.7 ± 0.3	0.0 ± 0.2	-0.1 ± 0.2
	$t_{F50\%}$ (ms)	7.1 ± 0.7	7.1 ± 0.7	7.4 ± 0.7	7.4 ± 0.7	0.0 ± 0.3	0.0 ± 0.3
	$t_{F90\%}$ (ms)	11.7 ± 0.7	11.6 ± 0.9	12.1 ± 0.8	12.1 ± 0.8	-0.2 ± 0.5	0.0 ± 0.3
	$t_{F50\text{-}90\%}$ (ms)	4.5 ± 0.4	4.4 ± 0.3	4.7 ± 0.3	4.7 ± 0.4	-0.1 ± 0.5	0.0 ± 0.2
	t_{200N} (ms)	2.9 ± 0.5	3.0 ± 0.5	3.1 ± 0.4	3.1 ± 0.4	0.1 ± 0.2	-0.1 ± 0.2
	t_{500N} (ms)	5.0 ± 0.7	5.2 ± 0.7	5.3 ± 0.7	5.4 ± 0.7	0.2 ± 0.3	0.1 ± 0.3
	F_{5ms} (N)	562 ± 90	547 ± 88	520 ± 97	508 ± 103	-15 ± 39	-13 ± 50
	F_{10ms} (N)	1451 ± 225	1365 ± 230 *	1360 ± 246 *	1317 ± 254	-86 ± 98	-43 ± 102
Lead hook	Peak force (N)	2569 ± 505	2432 ± 467 *	2482 ± 385	2443 ± 420	-138 ± 218	-44 ± 127
	Relative force ($N\cdot kg^{-1}$)	35.5 ± 3.7	33.6 ± 3.6 *	34.4 ± 3.2	34.3 ± 2.3	-1.9 ± 2.9	-0.7 ± 1.9
	Impulse (N·s)	16.1 ± 3.2	15.0 ± 3.7	16.2 ± 2.5	15.7 ± 2.7	-1.1 ± 2.9	-0.2 ± 2.1
	$t_{F10\%}$ (ms)	2.1 ± 0.5	2.1 ± 0.4	2.3 ± 0.5	2.1 ± 0.3	0.1 ± 0.1	-0.1 ± 0.1
	$t_{F50\%}$ (ms)	6.1 ± 1.4	6.3 ± 1.3	6.5 ± 1.4	6.2 ± 0.7	0.2 ± 0.4	0.0 ± 0.3
	$t_{F90\%}$ (ms)	9.9 ± 1.9	10.0 ± 2.0	10.3 ± 1.7	9.9 ± 1.1	0.2 ± 0.7	0.0 ± 0.3
	$t_{F50\text{-}90\%}$ (ms)	3.8 ± 0.6	3.8 ± 0.7	3.8 ± 0.4	3.8 ± 0.5	0.0 ± 0.4	-0.3 ± 1.3
	t_{200N} (ms)	1.8 ± 0.4	1.9 ± 0.4	1.9 ± 0.4	1.8 ± 0.4	0.1 ± 0.2	0.0 ± 0.2
	t_{500N} (ms)	3.3 ± 0.7	3.5 ± 0.7	3.6 ± 0.8	3.5 ± 0.5	0.2 ± 0.3	0.0 ± 0.2
	F_{5ms} (N)	1026 ± 260	928 ± 226 *	903 ± 238 *	923 ± 199	-97 ± 107	-13 ± 85 ǂ
	F_{10ms} (N)	2223 ± 587	1995 ± 546 *	2093 ± 406	2165 ± 360	-227 ± 357	1 ± 172 ǂ

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Table 4.1 continued

Rear hook	Peak force (N)	2737 ± 351	2528 ± 362 *	2663 ± 340	2569 ± 281	-209 ± 339	-67 ± 162
	Relative force ($N \cdot kg^{-1}$)	38.2 ± 4.6	35.4 ± 5.5 *	37.1 ± 4.3	36.1 ± 4.5	-2.8 ± 4.3	-0.8 ± 2.4
	Impulse (N·s)	16.9 ± 2.7	15.8 ± 3.4	18.1 ± 2.4	17.6 ± 2.0	-1.1 ± 3.4	-0.4 ± 1.2
	$t_{F10\%}$ (ms)	2.1 ± 0.3	2.0 ± 0.3	2.2 ± 0.4	2.2 ± 0.4	-0.1 ± 0.1	0.0 ± 0.1
	$t_{F50\%}$ (ms)	6.2 ± 0.8	6.1 ± 0.8	6.5 ± 0.9	6.6 ± 0.9	0.0 ± 0.4	0.2 ± 0.4
	$t_{F90\%}$ (ms)	10.4 ± 0.9	10.3 ± 0.9	10.9 ± 1.0	11.0 ± 1.1	-0.2 ± 0.6	0.3 ± 0.4
	$t_{F50\text{-}90\%}$ (ms)	4.3 ± 0.3	4.1 ± 0.4	4.4 ± 0.3	4.4 ± 0.4	-0.1 ± 0.4	-0.3 ± 1.2
	t_{200N} (ms)	1.6 ± 0.2	1.7 ± 0.3	1.8 ± 0.3	1.8 ± 0.3	0.1 ± 0.2	0.1 ± 0.2
	t_{500N} (ms)	3.1 ± 0.3	3.3 ± 0.5 *	3.5 ± 0.5 *	3.5 ± 0.6 ǂ	0.2 ± 0.3	0.2 ± 0.3
	F_{5ms} (N)	1048 ± 156	985 ± 193 *	945 ± 177 *	898 ± 196 ǂ	-63 ± 109	-63 ± 98
	F_{10ms} (N)	2318 ± 250	2146 ± 309 *	2180 ± 289 *	2048 ± 317 ǂ	-173 ± 273	-146 ± 218
Overall	Peak force (N)	1774 ± 285	1656 ± 259 *	1727 ± 258	1675 ± 231	-119 ± 158	-523 ± 95
	Relative force ($N \cdot kg^{-1}$)	24.6 ± 2.5	23.0 ± 2.2 *	24.0 ± 2.0	23.3 ± 2.4	-0.3 ± 1.0	0.1 ± 0.4
	Impulse (N·s)	12.7 ± 2.1	11.6 ± 2.3 *	12.9 ± 2.0	12.6 ± 1.7	-1.1 ± 2.1	-0.4 ± 0.8
	$t_{F10\%}$ (ms)	2.7 ± 0.5	2.6 ± 0.5	2.8 ± 0.5	2.7 ± 0.4	-0.1 ± 0.2	-0.1 ± 0.2
	$t_{F50\%}$ (ms)	7.0 ± 0.7	7.0 ± 0.8	7.3 ± 0.7	7.4 ± 0.7	-0.1 ± 0.3	0.1 ± 0.3
	$t_{F90\%}$ (ms)	11.5 ± 0.8	11.4 ± 1.0	12.0 ± 0.8	12.0 ± 0.8	-0.1 ± 0.5	0.1 ± 0.4
	$t_{F50\text{-}90\%}$ (ms)	4.4 ± 0.4	4.4 ± 0.3	5.0 ± 0.2	5.0 ± 0.3	0.0 ± 0.5	0.0 ± 0.2
	t_{200N} (ms)	3.3 ± 0.6	3.3 ± 0.5	3.4 ± 0.6	3.4 ± 0.6	0.0 ± 0.3	0.0 ± 0.2
	t_{500N} (ms)	5.6 ± 0.9	5.8 ± 0.8	5.9 ± 0.9 *	6.1 ± 0.8	0.2 ± 0.4	0.2 ± 0.4
	F_{5ms} (N)	594 ± 80	555 ± 52 *	545 ± 76 *	526 ± 66	-40 ± 55	-19 ± 39
	F_{10ms} (N)	1412 ± 231	1294 ± 170 *	1339 ± 187 *	1296 ± 166	-126 ± 150	-43 ± 81
Physiological response	Average heart rate (bpm)	169 ± 11	166 ± 9	160 ± 10	159 ± 10	-3 ± 4	-1 ± 6
	Peak heart rate (bpm)	180 ± 10	178 ± 8	172 ± 10	172 ± 9	-2 ± 4	0 ± 6
	RPE a.u.	15 ± 2	14 ± 3	15 ± 1	14 ± 2	0 ± 2	1 ± 1
	$[La^-]$ ($mmol \cdot L^{-1}$)	3.6 ± 1.5	2.9 ± 0.6 ‡	3.1 ± 0.5 *	3.0 ± 0.8	-0.7 ± 1.3	0.0 ± 0.7

Values are expressed as mean ± SD; * = significantly different from test 1; ǂ = significantly different from test 3; ‡ = significant interaction effect (day × test; changes between tests are significantly different on day 1 and two).

Table 4.2. Between-day reliability results for 3MPT trials over two days of testing.

		ICC (95% CI)	TE (95% CI)	SWC (0.2, 0.6 and 1.2)
Jab	Peak force (N)	-0.032 (-0.452 - 0.399)	91 (70 - 133)	26, 77, 155
	Relative force (N·kg^{-1})	-0.008 (-0.433 - 0.419)	1.2 (0.9 - 1.8)	0.3, 1.0, 2.0
	Impulse (N·s)	0.223 (-0.224 - 0.593)	0.8 (0.6 - 1.2)	0.2, 0.7, 1.4
	$t_{F10\%}$ (ms)	-0.372 (-0.689 - 0.063)	0.6 (0.4 - 0.8)	0.2, 0.5, 1.0
	$t_{F50\%}$ (ms)	-0.344 (-0.671 - 0.096)	0.8 (0.6 - 1.2)	0.2, 0.7, 1.4
	$t_{F90\%}$ (ms)	-0.241 (-0.605 - 0.206)	1.0 (0.7 - 1.4)	0.3, 0.8, 1.7
	$t_{F50\text{-}90\%}$ (ms)	0.461 (0.044 - 0.742)	0.4 (0.3 - 0.6)	0.1, 0.4, 0.7
	t_{200N} (ms)	-0.493 (-0.760 - -0.085)	0.7 (0.6 - 1.1)	0.2, 0.6, 1.2
	t_{500N} (ms)	-0.274 (-0.627 - 0.172)	1.1 (0.9 - 1.7)	0.3, 0.8, 2.0
	F_{5ms} (N)	-0.279 (-0.630 - 0.166)	36 (28 - 52)	10, 30, 61
	F_{10ms} (N)	-0.322 (-0.658 - 0.120)	90 (70 - 132)	26, 77, 153
Cross	Peak force (N)	-0.295 (-0.640 - 0.150)	127 (97 - 185)	36, 107, 215
	Relative force (N·kg^{-1})	-0.406 (-0.709 - 0.024)	1.9 (1.5 - 2.8)	0.6, 1.6, 3.3
	Impulse (N·s)	0.201 (-0.246 - 0.577)	1.5 (1.2 - 2.2)	0.4, 1.3, 2.6
	$t_{F10\%}$ (ms)	-0.475 (-0.749 - -0.062)	0.2 (0.2 - 0.3)	0.1, 0.2, 0.4
	$t_{F50\%}$ (ms)	-0.086 (-0.494 - 0.353)	0.3 (0.2 - 0.4)	0.1, 0.2, 0.5
	$t_{F90\%}$ (ms)	0.356 (-0.082 - 0.679)	0.4 (0.3 - 0.5)	0.1, 0.3, 0.6
	$t_{F50\text{-}90\%}$ (ms)	0.068 (-0.369 - 0.480)	0.3 (0.3 - 0.5)	0.1, 0.2, 0.4
	t_{200N} (ms)	-0.238 (-0.603 - 0.209)	0.2 (0.2 - 0.3)	0.1, 0.2, 0.4
	t_{500N} (ms)	-0.184 (-0.566 - 0.262)	0.3 (0.3 - 0.5)	0.1, 0.3, 0.6
	F_{5ms} (N)	-0.091 (-0.498 - 0.348)	47 (36 - 68)	13, 40, 79
	F_{10ms} (N)	-0.359 (-0.681 - 0.079)	116 (89 - 169)	33, 98, 197
Lead hook	Peak force (N)	0.073 (-0.398 - 0.495)	172 (131 - 256)	49, 146, 292
	Relative force (N·kg^{-1})	0.022 (-0.442 - 0.456)	2.5 (1.9 - 3.6)	0.7, 2.1, 4.2
	Impulse (N·s)	0.101 (-0.372 - 0.516)	2.5 (1.9 - 3.6)	0.7, 2.1, 4.2
	$t_{F10\%}$ (ms)	0.029 (-0.437 - 0.461)	0.2 (0.1 - 0.2)	0.0, 0.1, 0.3
	$t_{F50\%}$ (ms)	0.033 (-0.432 - 0.465)	0.3 (0.3 - 0.5)	0.1, 0.3, 0.6
	$t_{F90\%}$ (ms)	-0.279 (-0.669 - 0.190)	0.6 (0.5 - 0.9)	0.2, 0.5, 1.1
	$t_{F50\text{-}90\%}$ (ms)	0.004 (-0.457 - 0.442)	0.4 (0.3 - 0.6)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.337 (-0.132 - 0.673)	0.2 (0.1 - 0.2)	0.0, 0.1, 0.3
	t_{500N} (ms)	0.091 (-0.382 - 0.508)	0.3 (0.2 - 0.4)	0.1, 0.2, 0.43
	F_{5ms} (N)	0.254 (-0.223 - 0.620)	86 (66 - 128)	24, 73, 146
	F_{10ms} (N)	0.198 (-0.280 - 0.583)	255 (195 - 379)	72, 217, 434

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Table 4.2 continued

Rear hook	Peak force (N)	0.753 (0.451 - 0.893)	141 (106 - 213)	38, 115, 229
	Relative force (N·kg^{-1})	0.703 (0.360 - 0.870)	2.0 (1.5 - 3.1)	0.6, 1.7, 3.3
	Impulse (N·s)	0.451 (-0.031 - 0.740)	2.0 (1.5 - 3.0)	0.6, 1.7, 3.4
	$t_{F10\%}$ (ms)	0.013 (-0.511 - 0.460)	0.1 (0.1 - 0.2)	0.0, 0.1, 0.2
	$t_{F50\%}$ (ms)	-0.134 (-0.635 - 0.345)	0.4 (0.3 - 0.6)	0.1, 0.3, 0.6
	$t_{F90\%}$ (ms)	0.034 (-0.492 - 0.476)	0.5 (0.4 - 0.8)	0.1, 0.4, 0.8
	$t_{F50\text{-}90\%}$ (ms)	-0.418 (-0.757 - 0.041)	0.4 (0.3 - 0.6)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.483 (0.014 - 0.758)	0.1 (0.1 - 0.2)	0.0, 0.1, 0.2
	t_{500N} (ms)	0.377 (-0.127 - 0.698)	0.2 (0.2 - 0.3)	0.1, 0.2, 0.4
	F_{5ms} (N)	0.140 (-0.391 - 0.550)	97 (73 - 147)	27, 80, 159
	F_{10ms} (N)	0.547 (0.105 - 0.792)	172 (130 - 261)	47, 141, 281
Overall	Peak force (N)	0.110 (-0.332 - 0.512)	124 (95 - 181)	35, 105, 210
	Relative force (N·kg^{-1})	-0.074 (-0.485 - 0.363)	1.9 (1.4 - 2.7)	0.5, 1.6, 3.2
	Impulse (N·s)	0.257 (-0.190 - 0.616)	1.4 (1.1 - 2.0)	0.4, 1.2, 2.3
	$t_{F10\%}$ (ms)	-0.301 (-0.644 - 0.143)	0.2 (0.2 - 0.3)	0.1, 0.2, 0.4
	$t_{F50\%}$ (ms)	-0.101 (-0.505 - 0.339)	0.3 (0.3 - 0.5)	0.1, 0.3, 0.6
	$t_{F90\%}$ (ms)	0.163 (-0.282 - 0.551)	0.4 (0.3 - 0.6)	0.1, 0.3, 0.7
	$t_{F50\text{-}90\%}$ (ms)	0.238 (-0.209 - 0.603)	0.3 (0.2 - 0.4)	0.1, 0.3, 0.5
	t_{200N} (ms)	-0.382 (-0.695 - 0.052)	0.3 (0.2 - 0.5)	0.1, 0.3, 0.5
	t_{500N} (ms)	-0.024 (-0.445 - 0.406)	0.4 (0.3 - 0.6)	0.1, 0.3, 0.7
	F_{5ms} (N)	0.072 (-0.365 - 0.483)	46 (36 - 68)	13, 39, 78
	F_{10ms} (N)	0.131 (-0.313 - 0.527)	113 (867 - 165)	32, 96, 192
Physiological response	Average heart rate (bpm)	0.107 (-0.334 - 0.510)	5 (4 - 7)	5, 14, 27
	Peak heart rate (bpm)	0.038 (-0.395 - 0.456)	5 (4 - 7)	5, 14, 27
	RPE (a.u.)	0.655 (0.318 - 0.845)	1 (1 - 1)	0, 1, 2
	[La$^-$] (mmol·L^{-1})	-0.052 (-0.467 - 0.383)	1.0 (0.8 - 1.5)	0.3, 0.9, 1.8

Values are expressed as: TE = typical error; ICC = intraclass correlation coefficient; (95%CI) = 95% confidence interval; SWC = smallest worthwhile change for small (0.2), moderate (0.6) and large changes (1.2).

Table 4.3. Within-day reliability results for 3MPT performance on day one of testing.

		TE (95% CI)	CV (95% CI)	ICC (95% CI)	SWC (0.2, 0.6 and 1.2)
Jab	Peak force (N)	82 (63 - 119)	9.8 (7.5 - 14.6)	0.832 (0.629 - 0.929)	37, 112, 224
	Relative force ($N \cdot kg^{-1}$)	1.1 (0.8 - 1.6)	9.8 (7.5 - 14.6)	0.696 (0.384 - 0.865)	0.4, 1.1, 2.3
	Impulse (N·s)	0.8 (0.6 - 1.2)	13.3 (10.1 - 20.1)	0.786 (0.542 - 0.908)	0.3, 1.0, 2.0
	$t_{F10\%}$ (ms)	0.3 (0.3 - 0.5)	10.0 (7.6 - 15.0)	0.942 (0.862 - 0.976)	0.3, 0.7, 1.5
	$t_{F50\%}$ (ms)	0.5 (0.4 - 0.8)	6.5 (5.0 - 9.7)	0.912 (0.795 - 0.964)	0.3, 1.0, 2.0
	$t_{F90\%}$ (ms)	0.6 (0.5 - 0.9)	4.5 (3.4 - 6.6)	0.929 (0.832 - 0.971)	0.4, 1.2, 2.4
	$t_{F50\text{-}90\%}$ (ms)	0.5 (0.4 - 0.7)	14.9 (11.2 - 22.4)	0.593 (0.224 - 0.814)	0.1, 0.4, 0.9
	t_{200N} (ms)	0.4 (0.3 - 0.6)	7.6 (5.8 - 11.2)	0.932 (0.838 - 0.972)	0.3, 0.9, 1.7
	t_{500N} (ms)	0.6 (0.5 - 0.9)	7.3 (5.5 - 10.8)	0.938 (0.854 - 0.975)	0.4, 1.3, 2.6
	F_{5ms} (N)	25 (19 - 37)	9.4 (7.2 - 14.1)	0.940 (0.857 - 0.975)	19, 56, 112
	F_{10ms} (N)	70 (54 - 103)	10.6 (8.1 - 15.9)	0.881 (0.729 - 0.950)	38, 113, 227
Cross	Peak force (N)	80 (62 - 117)	4.9 (3.8 - 7.2)	0.951 (0.883 - 0.980)	66, 199, 397
	Relative force ($N \cdot kg^{-1}$)	1.2 (0.9 - 1.8)	4.9 (3.8 - 7.2)	0.850 (0.666 - 0.937)	0.6, 1.8, 3.5
	Impulse (N·s)	1.5 (1.2 - 2.2)	12.5 (9.5 - 18.7)	0.707 (0.403 - 0.871)	0.6, 1.6, 3.3
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	5.2 (3.9 - 7.6)	0.896 (0.761 - 0.957)	0.1, 0.2, 0.5
	$t_{F50\%}$ (ms)	0.2 (0.2 - 0.3)	2.9 (2.3 - 4.3)	0.927 (0.829 - 0.970)	0.1, 0.4, 0.8
	$t_{F90\%}$ (ms)	0.4 (0.3 - 0.5)	3.1 (2.4 - 4.6)	0.831 (0.627 - 0.928)	0.2, 0.5, 0.9
	$t_{F50\text{-}90\%}$ (ms)	0.3 (0.3 - 0.5)	7.8 (6.0 - 11.6)	0.107 (-0.334 - 0.510)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.1 (0.1 - 0.2)	4.8 (3.7 - 7.1)	0.930 (0.835 - 0.971)	0.1, 0.3, 0.6
	t_{500N} (ms)	0.2 (0.2 - 0.3)	4.2 (3.2 - 6.2)	0.915 (0.801 - 0.965)	0.1, 0.4, 0.8
	F_{5ms} (N)	27 (21 - 40)	5.0 (3.8 - 7.3)	0.920 (0.812 - 0.967)	18, 53, 105
	F_{10ms} (N)	70 (54 - 102)	5.2 (4.0 - 7.7)	0.920 (0.813 - 0.967)	46, 137, 274
Lead hook	Peak force (N)	154 (118 - 225)	6.5 (5.0 - 9.6)	0.914 (0.800 - 0.965)	97, 290, 580
	Relative force ($N \cdot kg^{-1}$)	2.1 (1.6 - 3.0)	6.5 (5.0 - 9.6)	0.699 (0.388 - 0.867)	0.7, 2.2, 4.4
	Impulse (N·s)	2.1 (1.6 - 3.0)	16.6 (12.5 - 25.1)	0.684 (0.364 - 0.860)	0.7, 2.1, 4.2
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	6.2 (4.7 - 9.2)	0.944 (0.867 - 0.977)	0.1, 0.3, 0.5
	$t_{F50\%}$ (ms)	0.3 (0.2 - 0.4)	4.7 (3.6 - 6.9)	0.966 (0.919 - 0.986)	0.3, 0.8, 1.6
	$t_{F90\%}$ (ms)	0.5 (0.4 - 0.7)	5.4 (4.1 - 7.9)	0.940 (0.857 - 0.975)	0.4, 1.1, 2.3
	$t_{F50\text{-}90\%}$ (ms)	0.3 (0.2 - 0.4)	7.5 (5.7 - 11.2)	0.838 (0.642 - 0.932)	0.1, 0.4, 0.7
	t_{200N} (ms)	0.1 (0.1 - 0.2)	7.9 (6.0 - 11.8)	0.906 (0.782 - 0.961)	0.4, 0.2, 0.5
	t_{500N} (ms)	0.2 (0.2 - 0.3)	6.0 (4.5 - 8.8)	0.924 (0.822 - 0.969)	0.1, 0.4, 0.8
	F_{5ms} (N)	76 (58 - 110)	8.6 (6.6 - 12.9)	0.918 (0.807 - 0.966)	49, 147, 293
	F_{10ms} (N)	252 (194 - 368)	14.4 (10.9 - 21.8)	0.826 (0.617 - 0.926)	114, 341, 683

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Table 4.3 continued

Rear hook	Peak force (N)	240 (184 - 350)	10.6 (8.0 - 15.8)	0.581 (0.206 - 0.807)	73, 220, 440
	Relative force (N·kg^{-1})	3.1 (2.4 - 4.5)	10.6 (8.0 - 15.8)	0.667 (0.336 - 0.851)	1.0, 3.1, 6.2
	Impulse (N·s)	2.4 (1.9 - 3.5)	17.2 (12.9 - 26.0)	0.401 (-0.030 - 0.707)	0.6, 1.8, 3.7
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.1)	3.5 (2.7 - 5.1)	0.966 (0.918 - 0.986)	0.1, 0.2, 0.4
	$t_{F50\%}$ (ms)	0.3 (0.2 - 0.4)	4.2 (3.2 - 6.2)	0.904 (0.777 - 0.960)	0.2, 0.5, 0.9
	$t_{F90\%}$ (ms)	0.4 (0.3 - 0.6)	4.2 (3.2 - 6.2)	0.785 (0.538 - 0.907)	0.2, 0.5, 1.0
	$t_{F50-90\%}$ (ms)	0.3 (0.2 - 0.4)	6.4 (4.9 - 9.5)	0.349 (-0.091 - 0.674)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.1 (0.1 - 0.2)	7.9 (6.0 - 11.8)	0.717 (0.419 - 0.876)	0.1, 0.2, 0.3
	t_{500N} (ms)	0.2 (0.2 - 0.3)	5.8 (4.5 - 8.6)	0.793 (0.554 - 0.911)	0.1, 0.3, 0.5
	F_{5ms} (N)	77 (59 - 112)	9.2 (7.0 - 13.8)	0.831 (0.626 - 0.928)	35, 105, 210
	F_{10ms} (N)	193 (148 - 281)	10.3 (7.8 - 15.4)	0.561 (0.177 - 0.797)	58, 174, 348
Overall	Peak force (N)	112 (86 - 163)	6.7 (5.1 - 10.0)	0.853 (0.671 - 0.938)	55, 165, 330
	Relative force (N·kg^{-1})	1.5 (1.2 - 2.3)	6.7 (5.1 - 10.0)	0.609 (0.247 - 0.822)	0.5, 1.5, 3.0
	Impulse (N·s)	1.5 (1.1 - 2.1)	13.8 (10.5 - 20.8)	0.596 (0.228 - 0.815)	0.5, 1.4, 2.7
	$t_{F10\%}$ (ms)	0.2 (0.1 - 0.2)	5.2 (4.0 - 7.7)	0.914 (0.799 - 0.964)	0.1, 0.3, 0.6
	$t_{F50\%}$ (ms)	0.2 (0.2 - 0.4)	3.3 (2.5 - 4.8)	0.913 (0.798 - 0.964)	0.2, 0.4, 0.9
	$t_{F90\%}$ (ms)	0.4 (0.3 - 0.5)	3.1 (2.4 - 4.6)	0.853 (0.672 - 0.938)	0.2, 0.5, 1.0
	$t_{F50-90\%}$ (ms)	0.3 (0.3 - 0.5)	8.3 (6.3 - 12.3)	0.054 (-0.381 - 0.469)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.2 (0.2- 0.3)	6.6 (5.0 - 9.7)	0.871 (0.708 - 0.946)	0.1, 0.3, 0.7
	t_{500N} (ms)	0.3 (0.2 - 0.4)	5.2 (3.9 - 7.6)	0.900 (0.768 - 0.958)	0.2, 0.5, 1.0
	F_{5ms} (N)	39 (30 - 57)	6.7 (5.1 - 9.9)	0.701 (0.392 - 0.868)	14, 42, 83
	F_{10ms} (N)	106 (82 - 155)	8.1 (6.1 - 12.0)	0.754 (0.484 - 0.893)	42, 125, 251
Physiological response	Average heart rate (bpm)	3 (2 - 4)	1.6 (1.3 - 2.4)	0.938 (0.852 - 0.974)	2, 6, 12
	Peak heart rate (bpm)	3 (2 - 4)	1.6 (1.2 - 2.3)	0.926 (0.826 - 0.970)	2, 5, 11
	RPE (a.u.)	1 (1 - 2)	9.9 (7.5 - 14.8)	0.798 (0.563 - 0.913)	0, 1, 3
	[La$^-$] (mmol·L^{-1})	0.9 (0.7 - 1.3)	23.4 (17.6 - 36)	0.402 (-0.028 - 0.707)	0.2, 0.7, 1.4

Values are expressed as: TE = typical error; CV = coefficient of variation; ICC = intraclass correlation coefficient; (95%CI) = 95% confidence interval; SWC = smallest worthwhile change for small (0.2), moderate (0.6) and large changes (1.2).

Table 4.4. Within-day reliability results for 3MPT performance on day two of testing.

		TE (95% CI)	CV (95% CI)	ICC (95% CI)	SWC (0.2, 0.6 and 1.2)
Jab	Peak force (N)	38 (29 - 55)	4.4 (3.4 - 6.5)	0.968 (0.922 - 0.987)	39, 116, 231
	Relative force (N·kg^{-1})	0.5 (0.4 - 0.7)	4.4 (3.4 - 6.5)	0.912 (0.795 - 0.964)	0.3, 0.9, 1.9
	Impulse (N·s)	0.4 (0.3 - 0.6)	6.3 (4.8 - 9.4)	0.948 (0.875 - 0.979)	0.3, 1.0, 2.0
	$t_{F10\%}$ (ms)	0.4 (0.3 - 0.5)	13.6 (10.3 - 20.4)	0.934 (0.844 - 0.973)	0.3, 0.8, 1.6
	$t_{F50\%}$ (ms)	0.5 (0.4 - 0.7)	7.0 (5.4 - 10.4)	0.936 (0.849 - 0.974)	0.4, 1.1, 2.1
	$t_{F90\%}$ (ms)	0.7 (0.5 - 1.0)	5.7 (4.3 - 8.4)	0.908 (0.787 - 0.962)	0.4, 1.2, 2.4
	$t_{F50-90\%}$ (ms)	0.3 (0.2 - 0.4)	5.2 (4.0 - 7.8)	0.667 (0.336 - 0.851)	0.1, 0.3, 0.5
	t_{200N} (ms)	0.4 (0.3 - 0.6)	9.2 (7.0 - 13.7)	0.927 (0.828 - 0.970)	0.3, 0.9, 1.7
	t_{500N} (ms)	0.9 (0.7 - 1.2)	10.6 (8.1 - 15.9)	0.878 (0.721 - 0.949)	0.5, 1.3, 2.7
	F_{5ms} (N)	20 (15 - 29)	8.7 (6.6 - 13.0)	0.946 (0.870 - 0.978)	15, 46, 91
	F_{10ms} (N)	36 (28 - 53)	6.7 (5.1 - 10.0)	0.963 (0.910 - 0.985)	34, 102, 205
Cross	Peak force (N)	79 (60 - 115)	5.1 (3.9 - 7.5)	0.958 (0.899 - 0.983)	69, 208, 417
	Relative force (N·kg^{-1})	1.1 (0.9 - 1.6)	5.1 (3.9 - 7.5)	0.912 (0.794 - 0.963)	0.7, 2.1, 4.2
	Impulse (N·s)	0.7 (0.5 - 1.0)	5.6 (4.3 - 8.2)	0.945 (0.869 - 0.978)	0.5, 1.6, 3.2
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	4.2 (3.2 - 6.2)	0.902 (0.774 - 0.960)	0.2, 0.2, 0.4
	$t_{F50\%}$ (ms)	0.2 (0.1 - 0.3)	2.5 (1.9 - 3.7)	0.939 (0.856 - 0.975)	0.1, 0.4, 0.8
	$t_{F90\%}$ (ms)	0.2 (0.2 - 0.4)	2.0 (1.5 - 2.9)	0.917 (0.807 - 0.966)	0.2, 0.5, 0.9
	$t_{F50-90\%}$ (ms)	0.2 (0.1 - 0.2)	3.0 (2.3 - 4.4)	0.828 (0.621 - 0.927)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.2 (0.1 - 0.2)	4.6 (3.5 - 6.7)	0.892 (0.752 - 0.955)	0.1, 0.3, 0.5
	t_{500N} (ms)	0.2 (0.2 - 0.3)	4.1 (3.1 - 6.0)	0.908 (0.786 - 0.962)	0.1, 0.4, 0.8
	F_{5ms} (N)	36 (27 - 52)	6.8 (5.2 - 10.1)	0.892 (0.751 - 0.955)	20, 59, 118
	F_{10ms} (N)	72 (56 - 106)	5.9 (4.5 - 8.7)	0.928 (0.831 - 0.971)	49, 148, 296
Lead hook	Peak force (N)	90 (69 - 134)	3.9 (2.9 - 5.8)	0.914 (0.800 - 0.965)	62, 187, 373
	Relative force (N·kg^{-1})	1.3 (1.0 - 2.0)	3.9 (2.9 - 5.8)	0.699 (0.388 - 0.867)	0.7, 2.6, 5.2
	Impulse (N·s)	1.5 (1.1 - 2.2)	8.3 (6.2 - 12.5)	0.684 (0.364 - 0.860)	0.4, 1.3, 2.7
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	4.6 (3.5 - 7.0)	0.944 (0.867 - 0.977)	0.1, 0.2, 0.5
	$t_{F50\%}$ (ms)	0.2 (0.2 - 0.3)	3.0 (2.3 - 4.5)	0.966 (0.919 - 0.986)	0.2, 0.5, 1.1
	$t_{F90\%}$ (ms)	0.2 (0.2 - 0.3)	2.3 (1.8 - 3.5)	0.940 (0.857 - 0.975)	0.2, 0.6, 1.2
	$t_{F50-90\%}$ (ms)	0.3 (0.2 - 0.4)	6.5 (4.9 - 9.8)	0.698 (0.372 - 0.868)	0.1, 0.3, 0.5
	t_{200N} (ms)	0.1 (0.1 - 0.2)	6.8 (5.2 - 10.3)	0.906 (0.782 - 0.961)	0.1, 0.2, 0.4
	t_{500N} (ms)	0.2 (0.1 - 0.2)	4.5 (3.4 - 6.8)	0.924 (0.822 - 0.969)	0.1, 0.3, 0.6
	F_{5ms} (N)	60 (46 - 90)	6.7 (5.0 - 10.0)	0.918 (0.807 - 0.966)	37, 111, 221
	F_{10ms} (N)	122 (93 - 180)	5.6 (4.2 - 8.4)	0.826 (0.617 - 0.926)	61, 183, 366

Continued on next page

Table 4.4 continued

Rear hook	Peak force (N)	115 (88 - 171)	4.9 (3.7 - 7.4)	0.581 (0.206 - 0.807)	80, 241, 481
	Relative force (N·kg^{-1})	1.7 (1.3 - 2.6)	4.9 (3.7 - 7.4)	0.667 (0.336 - 0.851)	0.6, 2.0, 3.8
	Impulse (N·s)	0.8 (0.6 - 1.2)	4.8 (3.6 - 7.2)	0.401 (-0.030 - 0.707)	0.5, 1.4, 2.9
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	4.7 (3.6 - 7.1)	0.966 (0.918 - 0.986)	0.1, 0.2, 0.4
	$t_{F50\%}$ (ms)	0.2 (0.2 - 0.4)	3.6 (2.7 - 5.3)	0.904 (0.777 - 0.960)	0.2, 0.5, 1.0
	$t_{F90\%}$ (ms)	0.3 (0.2 - 0.4)	2.3 (1.7 - 3.4)	0.940 (0.857 - 0.975)	0.2, 0.7, 1.3
	$t_{F50\text{-}90\%}$ (ms)	0.2 (0.2 - 0.3)	4.7 (3.6 - 7.1)	0.656 (0.301 - 0.847)	0.1, 0.2, 0.4
	t_{200N} (ms)	0.1 (0.1 - 0.2)	7.5 (5.7 - 11.4)	0.906 (0.782 - 0.961)	0.1, 0.3, 0.5
	t_{500N} (ms)	0.2 (0.1 - 0.3)	5.4 (4.1 - 8.1)	0.924 (0.822 - 0.969)	0.1, 0.4, 0.8
	F_{5ms} (N)	69 (53 - 103)	7.8 (5.9 - 11.8)	0.918 (0.807 - 0.966)	43, 128, 257
	F_{10ms} (N)	154 (118 - 229)	8.2 (6.2 - 12.5)	0.826 (0.617 - 0.926)	71, 213, 425
Overall	Peak force (N)	67 (52 - 98)	4.2 (3.2 - 6.2)	0.936 (0.849 - 0.974)	48, 145, 291
	Relative force (N·kg^{-1})	0.9 (0.7 - 1.4)	4.2 (3.2 - 6.2)	0.842 (0.650 - 0.933)	0.4, 1.3, 2.6
	Impulse (N·s)	0.6 (0.4 - 0.8)	4.7 (3.6 - 7.0)	0.918 (0.809 - 0.966)	0.4, 1.1, 2.2
	$t_{F10\%}$ (ms)	0.1 (0.1 - 0.2)	4.6 (3.5 - 6.8)	0.941 (0.859 - 0.976)	0.1, 0.3, 0.5
	$t_{F50\%}$ (ms)	0.2 (0.2 - 0.3)	2.9 (2.2 - 4.3)	0.935 (0.846 - 0.973)	0.1, 0.4, 0.9
	$t_{F90\%}$ (ms)	0.3 (0.2 - 0.4)	2.3 (1.7 - 3.3)	0.907 (0.785 - 0.962)	0.2, 0.5, 0.9
	$t_{F50\text{-}90\%}$ (ms)	0.1 (0.1 - 0.2)	2.3 (1.7 - 3.4)	0.809 (0.574 - 0.918)	0.0, 0.1, 0.3
	t_{200N} (ms)	0.2 (0.1 - 0.2)	4.6 (3.5 - 6.8)	0.936 (0.848 - 0.974)	0.1, 0.3, 0.7
	t_{500N} (ms)	0.3 (0.2 - 0.4)	4.6 (3.5 - 6.8)	0.920 (0.812 - 0.967)	0.2, 0.5, 1.0
	F_{5ms} (N)	28 (21 - 41)	5.1 (3.9 - 7.5)	0.866 (0.697 - 0.944)	14, 42, 85
	F_{10ms} (N)	57 (44 - 84)	4.4 (3.4 - 6.5)	0.909 (0.789 - 0.962)	35, 105, 210
Physiological response	Average heart rate (bpm)	4 (3 - 6)	2.7 (2.1 - 3.9)	0.872 (0.742 - 0.943)	2, 6, 12
	Peak heart rate (bpm)	1 (1 - 1)	6.4 (4.9 - 9.4)	0.722 (0.428 - 0.878)	0, 1, 2
	RPE (a.u.)	1 (1 - 1)	6.4 (4.9 - 9.4)	0.722 (0.428 - 0.878)	0, 1, 2
	[La$^-$] (mmol·L^{-1})	0.5 (0.4 - 0.7)	17.5 (13.2 - 26.5)	0.461 (0.044 - 0.742)	0.1, 0.4, 0.8

Values are expressed as: TE = typical error; CV = coefficient of variation; ICC = intraclass correlation coefficient; (95%CI) = 95% confidence interval; SWC = smallest worthwhile change for small (0.2), moderate (0.6) and large changes (1.2).

Table 4.5. Punch variables correlated with peak punch force.

Variable correlated with peak force (N)	*r* (95% CI)
$t_{F50\%}$ (ms)	0.323 (0.302 - 0.345) *
t_{500N} (ms)	0.707 (0.695 - 0.719) *
F_{5ms} (N)	0.891 (0.886 - 0.896) *
$t_{F50\text{-}90\%}$ (ms)	0.397 (0.376 - 0.417) *
Impulse (N·s)	0.918 (0.914 - 0.922) *

Values are correlation (*r*) and 95% confidence intervals (95% CI); * = correlation is significantly ($p < 0.001$) different from all other correlations.

4.4.2 Mechanical assessment

Force measured during incremental loading trials (Figure 4.4) was significantly correlated with theoretical force values ($r_s = 0.998$; $p < 0.001$ and ICC = 0.999; CI = 0.999 - 0.999; $p < 0.001$). Moreover, TE between measured and theoretical force values was 0.8 N (CL = 0.6 - 1.05 N) or 0.05% (CL = 0.04 - 0.07) when expressed as CV. There were significant correlations between forces measured in trial one and two on day one ($r_s = 0.995$; $p < 0.001$ and ICC = 0.999; CI = 0.999 - 0.999; $p < 0.001$) and trial one of day one and two ($r_s = 0.998$; $p < 0.001$ and ICC = 0.999; CI = 0.999 - 0.999; $p < 0.001$). Within-day TE and CV were 0.6 N (CL= 0.4 - 0.8 N) and 0.05% (CL = 0.04 - 0.07) respectively. Between-day TE and CV were 0.7 N (CL = 0.6 - 1.0) and 0.03% (CL = 0.03 - 0.05%) respectively. A one-way ANOVA indicated no significant differences ($p > 0.05$) between force measurements within-day, between-day, or between measured and theoretical values.

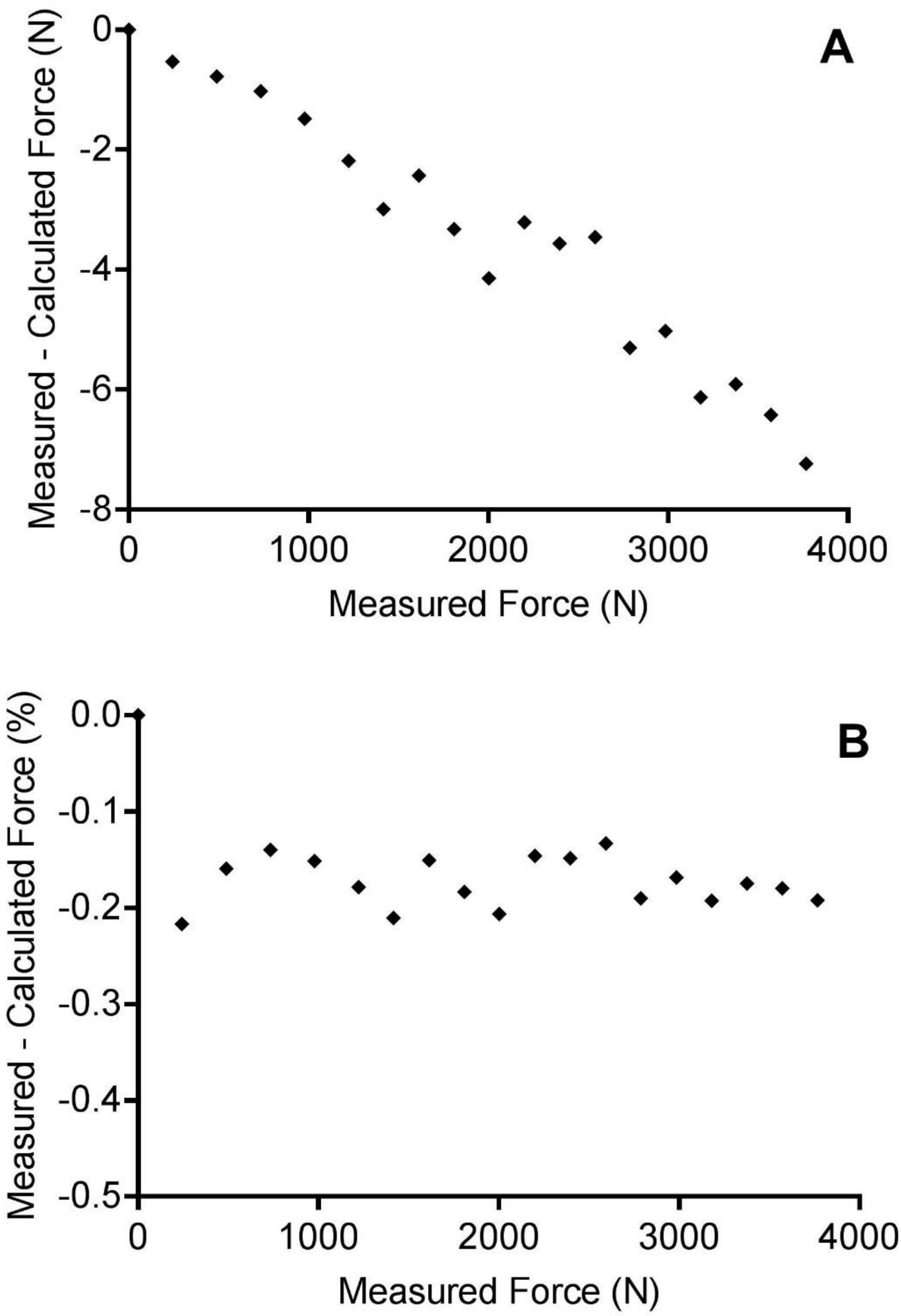

Figure 4.4. Data from the mechanical loading trial. Panel (A), the difference between measured force and force calculated from known masses plotted relative to force applied; panel (B), the difference between measured and calculated forces as a percentage of force measured plotted relative to force applied. The % error was consistent across loading magnitudes (B), and therefore the absolute error increased with load (A). Nonetheless, error was small compared to peak punch forces.

4.5 Discussion

Mechanical assessment of the PI revealed very good reliability and accuracy (< 0.1% error), allowing data from human performance trials to be interpreted with confidence. The 3MPT was performed by highly-trained male boxers to assess their capacity to punch for the equivalent of one round of boxing competition. Each punch type was examined separately, along with overall performance (all punch types). The results showed evidence of a learning effect, with reduced TE and CV on day two in many variables. Additionally, more variables showed significant differences between tests one and two on days one (18 variables) than day two (3 variables), and some showed significant test-by-day interaction effects on day one (mainly pertaining to lead-hand punches) but not day two. Finally, change scores from days one and two were not correlated, as indicated by very low ICC values. Although participants were familiarised with the test and were expert punchers, only one single test was completed for familiarisation, as opposed to repeated tests as completed on testing days. The physical and psychological demands (or perceptions thereof) of repeated tests were not familiar. It is therefore possible that participants were able to repeat their performance consistently on day two only after becoming familiar with repeated tests performed on day one. These data indicate a need for full familiarisation before the use of the PI and 3MPT, even in highly-trained boxers, to ensure high test reliability and to mitigate changes attributed to a learning effect.

3MPT reliability on day two was considered good (overall CV 2.3 - 5.1%). $SWC_{0.2}$ was smaller than TE for most variables, however given that TE was still less than $SWC_{0.6}$ the 3MPT can be considered useful for detecting moderate and large changes in performance (i.e. changes > 145 N overall; Table 4.4). Inclusion of relative (e.g. $t_{F50\%}$) and absolute (e.g. t_{500N}) indicators of RFD revealed interesting findings relating to the factors describing punch force, and may provide useful information about RFD under different performance conditions. Relative markers of RFD were very reliable (except $t_{F10\%}$, Table 4.3 and Table 4.4) but correlations between relative RFD and peak punch force were moderate (r = 0.323 - 0.397). Conversely, absolute RFD (i.e. F_{5ms}) variables were strongly correlated with peak punch force (r = 0.707 - 0.891) but showed more variability (however CVs were rarely > 10%). Therefore changes in one's ability to rapidly produce force against an object during punching, best indicated by absolute RFD, is more strongly associated with peak punch force than to relative RFD. Thus, measures of absolute RFD may provide meaningful information relating to punch effectiveness.

The characteristics of each punch type are important to identify in order to provide a holistic view of an individual's punching performance and better understand the way in which punch force is applied to a target. Rear- and lead-hand hooks produced the highest peak forces, followed by the cross and the jab, which is consistent with previous research [68]. Jabs also showed the poorest reliability with crosses showing the greatest. In boxing bouts, jabs may be used as a tactical or "setup" punch to create an opportunity for a subsequently delivered powerful cross or bent arm punch [65]. Even though the current participants were given consistent instructions to punch as hard and fast as possible, jabs might have been subconsciously used as a preparation technique before crosses, therefore showing higher performance variability [3]. Accordingly, focus of attention may influence punch force performance [100] and participants may have consciously or unconsciously focused their attention on crosses. While both lead-hand and rear-hand hooks were associated with acceptable force production reliability, lead-hand hooks were more reliable, while rear-hand hooks were more forceful than lead-hand hooks. The discrepancy in reliability may be due to lead-hand hooks being more commonly used in training and competition [22] while differences in peak force can be attributed to greater trunk rotation and centre of mass movement in rear-hand hooks compared to lead-hand hooks [1, 67]. Moreover, rear-hand hooks may inflict greater damage due to their ability to accelerate a body part (e.g. the head) or damage tissues [92]. Results of this study indicated that punch force and punch force variability are not directly related. However, the intent of punches (e.g. tactical verses damaging) and frequency of use in training or competition may play a role in the variability and magnitude of force produced. Based on these inferences, it is not possible to accurately speculate about the level of punch reliability for a population of inexperienced punchers, and this will need to be examined in future studies.

Considering that some variables included in this study were highly correlated to each other, some highly correlated and less reliable variables may be excluded in future studies. For example, t_{500N} may be used in place of t_{200N}, whilst F_{5ms} may be used instead of F_{10ms}, as these variable pairs were highly correlated and revealed similar information, yet the former showed higher reliability. Additionally, $t_{F10\%}$ showed significantly lower reliability than both $t_{F50\%}$ and $t_{F90\%}$, and therefore its exclusion is recommended. Based on this analysis, an abbreviated list of variables may be utilised to minimise information replication and limit the use of unreliable variables in performance testing in future studies.

In summary, the punch integrator had very good mechanical reliability and accuracy (error < 0.1%). For boxing trials a learning effect was observed in the 3MPT from day one to day two, however reliability on day two of testing was good. Therefore, participants may need a full repeated-trial session to minimise TE, particularly when observing changes in punch performance in response to acute or chronic interventions. Importantly, each punch type was associated with a different force-time profile and punch force reliability. This finding reinforces the need for comprehensive and specific reliability analyses so that the magnitude of change associated with meaningful or true change in punch impact characteristics are known for each punch type. These were potentially related to the frequency that punches were used in training or tactics typically associated with punches during competition. Regardless, based on the reliability outcomes the following force-time variables may be used in future studies: peak punch force, relative punch force, impulse, $t_{F50\%}$, $t_{F90\%}$, $t_{F50\text{-}90\%}$, t_{500N} and F_{5ms}. It is also essential that single punch and 3MPT reliability be determined in other (non-boxing) populations.

CHAPTER 5.

Relationships between punch impact force and upper- and lower-body muscular strength and power in highly-trained amateur boxers

Dunn, E.C., Humberstone, C.E., Franchini, E., Iredale, K.F. & Blazevich, A.J. Relationships between punch impact force and upper- and lower-body muscular strength and power in highly-trained amateur boxers. *In review: Journal of Strength and Conditioning Research,* 2019

5.1 Abstract

This study examined the relationship between upper- and lower-body strength and power characteristics and punch performance in 28 highly-trained male amateur boxers. Punch performance was assessed with a custom-built punch integrator using a 3-min maximal effort punch test that contained straight- and bent-arm punches from the lead and rear hands. Peak punch force and force-time variables including impulse and rate of force development (RFD; calculated to various points) were assessed. Force, power and RFD of the upper and lower body were assessed with countermovement bench throw, isometric bench push, countermovement jump (CMJ) and isometric mid-thigh pull (IMTP) tests. Correlation and regression analyses revealed significant ($p < 0.05$) relationships between peak punch force and forces measured in CMJ and IMTP tests. Additionally, peak punch force was significantly related to body mass, but RFD in the lower body was not. Moreover, no meaningful relationships between punch performance characteristics and any upper-body strength or power parameter were identified. The results of this study show that lower-body strength but not RFD was significantly and positively related to peak punch force production. While upper-body strength and power are expected to be important in boxing, they did not discriminate between boxers who punched with higher or lower peak force. Training that improves lower-body strength without increasing total body mass (to maintain weight category) may positively influence punch capacity in highly-trained amateur boxers.

5.2 Introduction

To achieve victory by knockout in boxing, an impact force of sufficient magnitude to accelerate the opponent's head to cause a momentary loss of consciousness is required [2, 70]. Alternatively, the repeated application of large impact forces throughout a boxing match increases the likelihood that the opponent's fighting capacity will be negatively affected, which increases the prospect of a points victory [5]. Thus, the ability to punch with a high impact force is advantageous for boxers [61]. Whilst increases in punch impact force should result from improvements in punch technique, they could also be achieved by increasing the physical capacities of the boxer [54]. Limited research has examined the association between boxer physical characteristics and punch force production so it is unclear whether it has a meaningful influence [1]. Punching is a high-speed movement where muscular force is required to accelerate the arm. Therefore, theoretically, muscular strength as well as high rates of force development (resulting in increased acceleration, and thus punch power, i.e. force at high movement velocity) should be key factors affecting punch force application [12]. However, there is a lack of detailed research describing the relationship between force production capacity and punch force.

The force of a punch is delivered to the opponent by the arm of the puncher, so it makes sense that force production characteristics of the arm would critically influence punch impact force [69]. However, immediately prior to a punch a boxer typically has minimal horizontal momentum, so force production by the feet against the ground is required to initiate forward momentum and provide the conditions for a subsequent rapid arm extension and high punch impact force [19]. Thus, the first event in the punch is the delivery of force by the lower limbs to the ground, and lower-limb force production might therefore be considered to be important for subsequent punch impact force production [4]. Recently, Loturco et al. [12] found that mean propulsive power in bench throw and bench push tests as well as the maximum isometric force in a half squat test were associated with the impact force measured in single jab and cross punches. The researchers tested an elite sample of boxers who were similarly skilled, however the inclusion of both male and female boxers within the analysis may have increased between-subject variability and subsequently led to correlation coefficient inflation. Previous to this, no investigations had examined associations between punch impact force and muscular strength and power characteristics, although some researchers found indirect links by comparing boxing or punching performance and selected muscular strength and power attributes [7, 101]. For example, Smith et al. [7] were able to differentiate between novice-, intermediate- and elite-level amateur boxers by their punch impact forces, which were attributed to a greater leg drive and rotational force production in the elite group. However, it is not clear whether other non-technical factors, such as upper- or lower-body strength, power or rate of force development, might have influenced punch force.

Preliminary work by Filimonov et al. [64] assessed the technical aspects contributing to straight rear-hand punches. While the calculation methods used to quantify segmental contributions are not specified and force magnitudes are not reported, the researchers concluded that the most experienced boxers, as well as the boxers with the greatest punch impact forces, effectively utilised greater coordination of the body segments and leg drive. Further, Smith [5] subsequently compared lead- and rear-hand straight punch forces and theorised that greater forces in the rear hand were a result of greater trunk rotation and lower-body contribution. Also, Lenetsky et al. [4] reviewed the key factors influencing punch force, incorporating literature from striking combat sports as well as sports with similar movement patterns such as shot put and javelin, and concluded that leg strength, particularly in the transverse plane (i.e. horizontal ground reaction force) is an important conditioning focus for increasing straight rear-hand punch force. Collectively, the literature concerning physical and technical aspects of punch force production indicates that force production in the lower body may be important, although specific research showing this is scarce.

As highlighted by Lenetsky et al. [102], limited research has examined the relationship between muscular strength and power (and rate of force development) and punch impact force. Whilst indirect evidence links muscular strength and power characteristics to punch impact force production, only one study has explicitly examined this link [12], and it may be that heterogeneity of the participant sample influenced the strong relationships observed. The purpose of the present research, therefore, was to examine the relationship between muscular strength, power and rate of force development characteristics of the upper and lower limbs and punch performance in a homogeneous sample of highly-trained amateur boxers. The hypothesis of the present study was that significant and positive relationships would be found between punching performance and the upper- and lower-body muscular strength and power characteristics of highly-trained boxers.

5.3 Methods

5.3.1 Experimental approach to the problem

A single cohort, cross-sectional study was conducted to investigate the relationships between punch impact force characteristics and performances in four tests of muscle function: countermovement bench throw (CMBT), isometric bench push (IBP), countermovement jump (CMJ) and isometric mid-thigh pull (IMTP). These four tests were chosen to assess the physical strength and power of the boxers upper and lower bodies as they are simple to administer and have previously been shown to be reliable and accurate for an athletic population [73]. The whole cohort of participants was included in the correlational analysis, and boxers were retrospectively allocated into three groups according to punch force performance test scores and between-group comparisons of their physical qualities were conducted.

5.3.2 Participants

Twenty-eight highly-trained male amateur boxers aged 19 ± 2 years (age range 16 - 24 years; height 177.3 ± 7.3 cm; body mass 70.5 ± 11.7 kg) participated in this study. Participants attended a camp with Boxing Australia, at the Australian Institute of Sport (Canberra, Australia). All participants gave voluntary informed consent before taking part in this study and were made aware that they could withdraw their data at any time. A parent or guardian provided informed consent for participants under 18 years. The study was approved by Edith Cowan University Human Research Ethics Committee (ID: 12233) and conducted in accordance with the Declaration of Helsinki.

5.3.3 Procedures

All participants completed familiarisation sessions for the physical as well as punch performance tests to gain experience with the assessment protocols in the days prior to official testing. The respective familiarisation sessions involved participants completing each test exactly as outlined for official testing sessions. Testing sessions were conducted on two separate days, with no more than one week between sessions; the first for physical testing and the second for punch performance testing. Immediately prior to the physical testing session (session 1) participants performed a standardised warm-up including 5 min of steady-state cycling (at a low intensity), dynamic stretches, body-weight squats, and test-specific movements, e.g. countermovement jumps or bench press. Prior to the boxing-specific testing session (session 2) the participants completed a standardised, boxing-specific warm-up including low-intensity steady-state aerobic activity (rowing), dynamic stretches, and punching bag work at increasing intensities. For the physical testing session ground reaction force, bar displacement (for dynamic movements) and time variables were collected using a 795 × 795 mm force platform (400 Series Force Plate; Fitness Technology, Adelaide, Australia) and a linear position transducer (PT 9510; Celesco, Canoga Park, USA) sampling at 600 Hz without prior filtering. Data were collected with an interface from commercially available software (Ballistic Measurement System; Innervations, Perth, Australia; Version 2015.0.0). The system was calibrated according to the manufacturer's instructions before data collection began. Lower-body tests were completed before upper-body tests, and dynamic tests preceded isometric. All physical tests were selected and performed in accordance with the best practice guidelines at the Australian Institute of Sport [103].

5.3.3.1 Countermovement bench throw (CMBT)

A flat, padded bench was positioned on top of the force platform and located underneath a Smith Machine (Plyometric Technologies, Lismore, Australia). The Smith Machine bar was aligned with the centre of the force platform. Participants completed five maximal bench throws. The linear position transducer was fixed to the bar with a Velcro strap. The participants lay supine on the bench with their knees flexed to 90° and feet resting on the bench. The 19.5-kg bar was positioned 2 cm superior to the xiphoid process. Participants placed their hands on the bar so that they were in their self-determined "strongest position". The test was started with full elbow extension, and the participants then lowered the bar to their chest at a self-selected speed and threw the bar for maximal height with no pause between lowering and throwing phases [73]. From the force- and displacement-time data, peak force (newtons; F_{CMBT}) and peak power (watts; P_{CMBT}) were calculated. The average of the best three throws for each participant was retained for analysis. The technique described has been shown to have good reliability (peak force intraclass correlations coefficient = 0.92 and coefficient of variation = 2.9% [104]).

5.3.3.2 Isometric bench push (IBP)

The participant setup procedure was identical to that of the bench throw test (described above), however the bar was fixed at a height above the participant's chest at which the elbows were flexed to 90°. The bar was loaded with sufficient weights to render it immovable. The participants were instructed to push as hard and fast as possible for 5 s in order to exert a maximal force against the bar in an isometric contraction, and were given a 2-min rest between trials. From the force-time data collected, the rate of force development was measured in the interval 0 - 250 ms, where 0 = onset of force above baseline ($N \cdot s^{-1}$; RFD_{IBP}; 0 - 250 ms); this time interval was chosen as it was similar to the time taken to deliver a forceful punch [65, 105]. Using previously described methods, visual determination was used to identify onset of force above baseline as the time point at which "the last trough before force deflects above the range of the baseline noise" occurred [106, 107]. Peak force (F_{IBP}) was taken from the unsmoothed data as an average of the force during the peak of the contraction over a 1-s time interval (usually occurring between 2 - 4 seconds). Rate of force development normalised to peak force was also calculated (%RFD_{IBP}). After test completion, within-subject reliability was assessed. While most of the data met an appropriate level of reliability (intraclass correlation coefficient [$ICC_{1,3}$] > 0.8, consistent with previous research where $ICC_{1,3}$ = 0.89 and coefficient of variation = 1.6% for peak force [104]), CV for RFD_{IBP} was very large (CV > 20%). Due to these large within-subject variations, the single best trial for each participant was used for subsequent statistical analysis. Data corruption recognised after the completion of the experiment, meant that data for only 13 participants could be analysed for this test. Therefore, IBP variables were not included in the between-group comparison. As the data were collected during a boxing high-performance camp (Australian Institute of Sport, Canberra, Australia) scheduling constraints meant that it was not possible to re-collect the data.

5.3.3.3 Countermovement jump (CMJ)

Participants performed five unloaded maximal effort CMJs on the force platform whilst holding an aluminium bar across their shoulders. The linear position transducer was tethered to the aluminium bar and captured jump height (centimetres; h_{CMJ}), peak power (P_{CMJ}) and peak force (F_{CMJ}). Participants were instructed to jump for maximum height immediately after squatting to a self-selected countermovement depth [73]. The average of the three best jumps for each participant was selected for analysis. The technique described has been shown to have good reliability (peak force intraclass correlations coefficient = 0.96 and coefficient of variation = 3.5% [73]).

5.3.3.4 Isometric mid-thigh pull (IMTP)

Participants performed two maximal IMTP exertions whilst standing on the force platform. The participants grasped an immovable steel bar set at a height such that the arms and back were straight with a hip angle 15 - 25° and knee angle 45 - 55°, where 0° = full extension [73]. The participants were instructed to pull up on the bar as hard and as fast as possible for 5 s in order to exert maximal force on the bar in an isometric contraction. Participants were given 2 min of rest between trials. From force-time data, peak force (F_{IMTP}) and rate of force development (0 - 250 ms; RFD_{IMTP}) were calculated as described above. Rate of force development normalised to peak force (%RFD_{IMTP}) and peak force relative to body mass (F_{IMTP}/BM) were also calculated. While most of the data met an appropriate level of reliability ($ICC_{1,3}$ > 0.8; consistent with previous research where $ICC_{1,3}$ = 0.97and CV = 2.4%) [73]), the CV for RFD_{IMTP} was very large (CV > 20%). Due to these large within-subject variations, the single best trial for each participant was used for subsequent statistical analysis [108].

5.3.3.5 Boxing-specific punch performance test

Participants completed a standardised, boxing-specific warm-up including low-intensity steady-state aerobic activity (rowing), dynamic stretches, and punching bag work at increasing intensities, before completing a 3-min punch test (3MPT) on the punch integrator (described below). The 3MPT includes short combinations of both straight and bent arm punches delivered from a self-selected distance from a fixed, vertical pad at maximum intensity (as in Study 2). The punch integrator was used to measure punch forces (newtons) via a wall-mounted S-beam load cell (KAC-E, Angewandte System Technik Gruppe, Germany) in series with the punch pad, which was set at the height of each participant's fist when their arm was extended horizontally. The following variables were extracted or calculated from the punch integrator using custom software and according to previously-described methods (Study 2): impulse generated to the point of peak force (N·s; impulse), peak punch force relative to body mass ($N \cdot kg^{-1}$); relative punch force), time to 50% of peak force (ms; $t_{F50\%}$), time to 90% of peak force (ms; $t_{F90\%}$), time from 50% to 90% of peak force (ms; $t_{F50\text{-}90\%}$), time to 500 N (ms; t_{500N}), and force at 5 ms (N; F_{5ms}). These variables were identified (in Study 2) amongst a larger set of variables to describe punch impact force production with minimal information replication (i.e. reduced inter-correlation) and good reliability. The average of all punches identified by the custom analysis software for each participant was used for statistical analysis. All trials were conducted in thermoneutral conditions (23.6 ± 1.4 °C, 36.3 ± 4.3% relative humidity; 94.5 ± 0.2 kPa).

5.3.4 Statistical analysis

Data were analysed using IBM SPSS Statistics (version 19) and expressed as mean ± SD. Pearson's correlation coefficients (*r*) were computed to assess the linear relationships between punch performance variables and physical characteristics. Three regression analyses were conducted to assess the relationship between variables describing the physical characteristics of the boxers and the punch force variables. A multiple regression was conducted to assess the relationship between peak punch force and both CMJ peak force and IMTP peak force in combination and two linear regressions were conducted to assess the relationship between peak punch force and CMJ peak force and IMTP peak force separately.

These models were selected after correlation analyses revealed that these variables had strong and significant relationships with punch performance (see results). The participants were also split into three groups based on their peak punch forces. The top 10 boxers were categorised as high force (HF; 95% confidence interval [95%CI] = 2081 - 2529 N), the bottom 10 as low force (LF; 95% CI = 1463 - 1663 N), and the remaining eight as medium force (MF; 95%CI = 1791 - 1936 N) punchers. A one-way analysis of variance (ANOVA) was used to test for differences in physical characteristics between HF, MF and LF groups. For all significance testing, alpha was set at $p < 0.05$. Where significant effects were observed, Fisher's Least Significant Difference [109] correction was applied to post-hoc analyses to identify where differences occurred. Cohen's *d* was calculated to indicate the effect size (ES) of significant between-group differences, and interpreted according to Rhea [83].

5.4 Results

Significant correlations between punch performance variables and the strength and power assessment variables are shown in Table 5.1. Correlations between selected upper-and lower-body strength and power characteristics and punch force are shown in Figure 5.1. Regression analysis to predict peak punch force from CMJ peak force and IMTP peak force revealed that separately, F_{CMJ} [(F (54, 27) = 22.675, $p < 0.001$, $R^2 = 0.466$, i.e. $Punch\ Force = 607 + 0.756\ \times (F_{CMJ})$] and F_{IMTP} [(F (25, 27) = 21.475, $p < 0.001$, $R^2 = 0.462$ i.e. $Punch\ Force = 194 + 0.737\ \times (F_{IMTP})$] significantly predicted peak punch force. Additionally, a multiple regression revealed that together F_{CMJ} and F_{IMTP} significantly predicted peak punch force [F (24, 26) = 13.009, $p < 0.001$, $R^2 = 0.520$; i.e. $Punch\ Force = 212 + 0.42\ \times (F_{CMJ}) + 0.419\ \times (F_{IMTP})$], however, in contrast to the single variable regressions, neither F_{CMJ} nor F_{IMTP} contributed significantly to the strength of the equation (p = 0.096; p = 0.101, respectively).

Results of the physical characteristics assessment are shown in Table 5.2. Compared to LF, F_{CMJ} and $\%RFD_{IMTP}$ were significantly higher in MF (p = 0.016, ES = 1.43; p = 0.007, ES = 1.66, respectively) and HF ($p < 0.001$, ES =1.72; p = 0.013, ES =1.18, respectively). Peak force in IMTP was significantly higher in HF compared to LF ($p < 0.001$, ES = 2.09) and MF (p =

0.011, ES = 1.35) and P_{CMJ} was significantly greater in HF compared to LF (*p* = 0.010, ES = 1.23). Peak punch force was significantly higher in HF compared to LF (*p* < 0.001, ES = 3.24) and MF (*p* < 0.001, ES = 1.92), and MF was also greater than LF (*p* = 0.003, ES = 3.20). Similarly, impulse and F_{5ms} were significantly higher in HF compared to LF (*p* < 0.001, ES = 3.40; *p* < 0.001, ES = 3.09, respectively) and MF (*p* < 0.001, ES = 2.28; *p* < 0.001, ES = 1.99, respectively), and MF was greater than LF (*p* = 0.005, ES = 2.09; *p* = 0.007, ES = 1.60, respectively). Relative punch force was significantly greater in HF compared to LF (*p* = 0.017, ES = 1.08), and t_{500N} was significantly slower in LF compared to MF (*p* = 0.002, ES = 1.53) and HF (*p* < 0.001, ES = 1.80).

Table 5.1. Correlation coefficients computed between boxers' physical characteristics and punch force characteristics.

	Peak force (N)	Relative force (N\kg)	Impulse (N·s)	F_{5ms} (N)	t_{500N} (ms)
Mass (kg)	0.604 ** (0.298 - 0.797)	-0.227 (-0.553 - 0.160)	0.638 *** (0.348 - 0.817)	0.502 ** (0.159 - 0.737)	-0.349 (-0.639 - 0.028)
F_{IBP} (N)	0.141 (-0.445 - 0.642)	-0.615 * (-0.871 - -0.097)	0.137 (-0.448 - 0.640)	0.073 (-0.498 - 0.600)	-0.216 (-0.380 - 0.685)
F_{IMTP} (N)	0.680 *** (0.411 - 0.840)	0.128 (-0.257 - 0.478)	0.679 *** (0.410 - 0.839)	0.680 *** (0.411 - 0.840)	-0.588 ** (-0.788 - -0.275)
F_{IMTP}/BM (N·kg^{-1})	0.081 (-0.301 - 0.441)	0.472 * (0.120 - 0.719)	0.020 (-0.356 - 0.390)	0.281 (-0.103 - 0.592)	-0.352 * (-0.641 - 0.024)
%RFD_{IMTP} (%N·s^{-1})	-0.524 ** (-0.750 - -0.188)	-0.297 (-0.603 - 0.086)	-0.509 ** (-0.741 - -0.168)	-0.379 (-0.659 - -0.007)	0.270 (-0.115 - 0.584)
F_{CMJ} (N)	0.683 *** (0.416 - 0.842)	0.087 (-0.296 - 0.446)	0.664 *** (0.387 - 0.831)	0.606 ** (0.301 - 0.799)	-0.599 ** (-0.795 - -0.291)
P_{CMJ} (W)	0.538 ** (0.206 - 0.759)	-0.136 (-0.484 - 0.250)	0.528 ** (0.193 - 0.753)	0.505 ** (0.163 - 0.739)	-0.348 (-0.638 - 0.029)

Values are expressed as Pearson's *r* (95% CI); * = correlation is significant (*p* < 0.05); ** = (*p* < 0.01); *** = (*p* < 0.001).

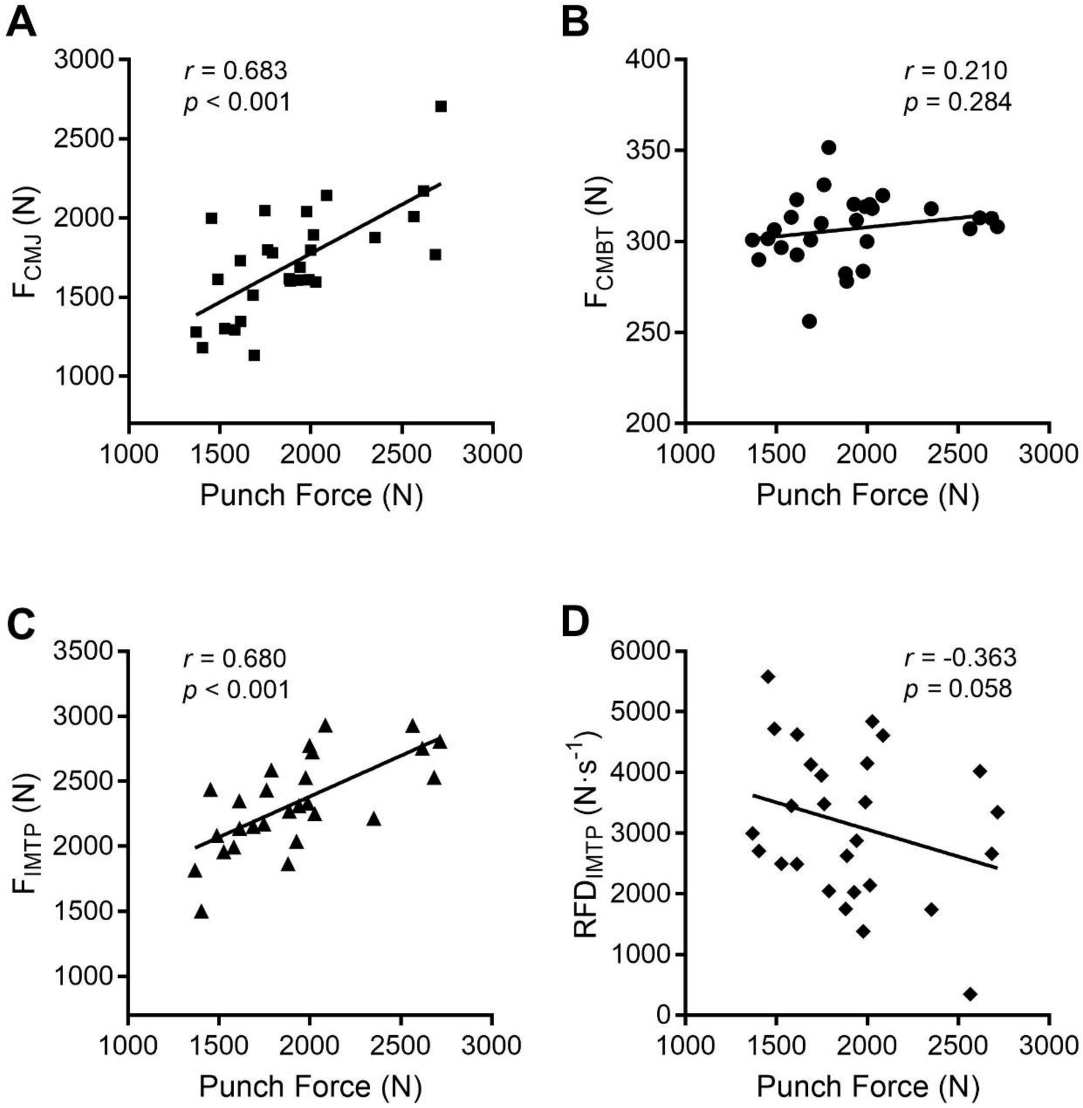

Figure 5.1. Correlations between punch impact force and muscular strength and power characteristics. Panel (A) countermovement jump force; F_{CMJ}, (B) countermovement bench throw force; F_{CMBT}, (C) isometric mid-thigh pull force; F_{IMTP}, and (D) isometric mid-thigh pull rate of force development; RFD_{IMTP}. Punch force was positively correlated with lower-body force measures (F_{CMJ}; [A] and F_{IMTP}; [C]), however no clear relationships were found between punch force and upper-body force measures (F_{CMBT}; [B]) or lower-body rate of force development (RFD_{IMTP}; [D]).

Table 5.2. Overall punch force characteristics of low, medium, and high punch force groups.

	Low force (n = 10)	Medium force (n = 8)	High force (n = 10)
Body mass (kg)	61.8 ± 9.4	71.5 ± 7.7	78.4 ± 11.0 *
F_{CMBT} (N)	298 ± 18	309 ± 26	314 ± 8
P_{CMBT} (W)	388 ± 75	464 ± 121	479 ± 31
F_{IBP} (N)‡	677 ± 65	879 ± 130	679 ± 131
RFD_{IBP} (N·s^{-1}) ‡	1481 ± 250	1669 ± 484	1761 ± 507
%RFD_{IBP} (%N·s^{-1}) ‡	2.2 ± 0.4	1.9 ± 0.4	2.6 ± 0.3
F_{IMTP} (N)	2048 ± 280	2275 ± 245	2626 ± 273 * ǂ
F_{IMTP}/BM (N·kg^{-1})	33.2 ± 4.0	32.0 ± 2.9	33.8 ± 4.2
RFD_{IMTP} (N·s^{-1})	3690 ± 1123	2518 ± 883	3138 ± 1416
%RFD_{IMTP} (%N·s^{-1})	1.8 ± 0.4	1.1 ± 0.4 *	1.2 ± 0.6 *
F_{CMJ} (N)	1438 ± 273	1772 ± 184 *	1957 ± 328 *
P_{CMJ} (W)	3142 ± 702	3804 ± 708	4087 ± 830 *
h_{CMJ} (cm)	41 ± 4	42 ± 0.7	42 ± 5
Punch force (N)	1543 ± 112	1864 ± 87 *	2305 ± 313 * ǂ
Relative force (N·kg^{-1})	25.1 ± 3.7	26.2 ± 3.2	29.7 ± 4.8 *
Impulse (N·s)	10.9 ± 0.9	12.5 ± 0.6 *	15.1 ± 1.5 * ǂ
$t_{F50\%}$ (ms)	7.0 ± 1.0	6.9 ± 0.6	7.3 ± 0.9
$t_{F90\%}$ (ms)	11.8 ± 1.3	11.6 ± 1.2	11.9 ± 1.0
$t_{F50\text{-}90\%}$ (ms)	4.8 ± 0.8	4.7 ± 0.7	4.6 ± 0.7
F_{5ms} (N)	539 ± 71	640 ± 54 *	784 ± 87 * ǂ
t_{500N} (ms)	5.7 ± 0.9	4.5 ± 0.7 *	4.4 ± 0.6 *

Values are expressed as mean ± SD; * = significantly different from low force group ($p < 0.05$); ǂ = significantly different from medium force group ($p < 0.05$); ‡ = due to reduced sample sizes for this test (n = 13) IBP variables were not included in the group comparison analysis; CMBT = countermovement bench throw; IBP = isometric bench push; IMTP = isometric mid-thigh pull; CMJ = countermovement jump.

5.5 Discussion

The ability to punch with a high impact force is an important attribute for boxers; a single substantial blow can result in a win by knockout and continual effective blows exert dominance and allow a boxer to achieve success [61, 93]. As such, understanding the physical characteristics that are associated with forceful punching is important in order to develop training strategies to improve punch performance. The present study investigated the relationships between punch force characteristics and strength and power characteristics of the upper and lower body in highly-trained amateur boxers. The main findings were that positive relationships existed between punch characteristics (punch force, impulse and force at 5 ms [F_{5ms}]) and lower-body strength characteristics, but not lower-body rate of force development or characteristics pertaining to strength or power of the upper body. The positive relationship between peak punch force and lower-body strength was illustrated (Figure 5.1) by positive correlations between peak punch force and both countermovement jump force (F_{CMJ}) and isometric mid-thigh pull force (F_{IMTP}) as well as significant differences between boxers with the highest punch forces (HF) and lowest punch forces (LF; see Table 5.2). The relationship between lower-body strength and punch force observed in the present study is consistent with the findings of Loturco et al. [12]. Peak power produced in the CMJ was also related to punch force, impulse and F_{5ms}, however lower-body rate of force development measured in the IMTP test was poorly correlated with punch force characteristics; a lower reliability of the RFD measurement in the IMTP test may have reduced the likelihood of finding significant correlations.

These findings are consistent with the idea that the lower limbs generate significant ground reaction forces throughout the duration of the punch [64], and that this force provides the momentum available for transfer to the arm and hand for punching [4]. In this case the rate of force production may be less important than the production of larger, sustained (e.g. > 250 ms) force. To determine whether RFD_{IMTP} might have been more associated with peak punch force once normalised to peak leg strength (i.e. measured in the IMTP), the normalised RFD ($\%RFD_{IMTP}$) was correlated with peak force. The negative correlation indicated a distinct lack of positive influence of RFD on punch force. It was also noted that heavier boxers were stronger and that body mass rather than strength may have been a key factor. Once normalised to body mass, peak force in the IMTP test was no longer correlated with punch force. Thus, the greater strength in boxers with higher punch force possibly results, at least partly, from them having a greater (muscle) mass. Such a relationship between body mass and punching force has been reported previously by various researchers [5, 6, 12, 70]. Since boxers contest fights in weight categories, however, increasing mass (e.g. through hypertrophic training practices) is rarely an option for boxers [71]. Thus the use of methods that increase lower-limb strength without significant body mass gain may be of great benefit. This idea is consistent with the present finding of a moderate and significant correlation between peak IMTP force normalised to body mass and peak punch force relative to body mass (Table 5.1).

In the present study, no significant or practically meaningful relationships were observed between punch force characteristics and upper-body strength and power properties. Correlation analysis revealed no relationship between peak isometric strength tested by IBP and peak punch force (and only a moderate negative relationship with punch force relative to body mass). Nonetheless, in a previous study, a significant relationship between punch force and upper-body strength was observed [12]. However, in that study a heterogeneous cohort consisting of both male and female boxers was examined. These increases in variability may have increased the likelihood of identifying discriminating physical factors relating to punch force (i.e. correlation inflation). However, strength and power in the upper body are undoubtedly important for delivering a forceful punch. Previous research that examined muscle activation patterns during striking has shown that expert strikers are able to maximise strike speed and impact force by using rapid and coordinated muscle activation and deactivation in the striking limb [110]. Furthermore, increasing the rigidity of the striking limb through muscle contraction only just prior to impact reduces the amount of energy lost in the collision, allowing a greater transfer of momentum to the opponent [102, 110, 111]. These findings indicate that the musculature of the upper body is important for maximising the force of impact, irrespective of expertise level, as it is necessary to achieve limb rigidity upon impact. Thus, in a homogeneous sample of highly-trained boxers, such as the present study, upper-body strength and power characteristics may not be discriminating factors relating to punch force, yet these traits are probably still important for the delivery of a punch.

In summary the results of the present study suggest that lower-limb strength is strongly related to peak punch force production in well-trained boxers and may be a key contributor to the delivery of a high force punch. Whilst lower-limb strength measures were able to discriminate between the most and least forceful punchers in a cohort of highly-trained male boxers, lower-limb power and rate of force development and upper-body strength and power provided no discriminatory ability. While it cannot be discounted that these qualities are important to punch force capacity, they do not appear to be primary targets for development in well-trained boxers.

5.5.1 Practical applications

The results of this study suggest that a greater leg strength may allow for higher peak punch force in highly-trained male boxers, possibly because a higher ground reaction force can be generated and thus forward momentum can be developed. It is possible that in such a population, trainers and coaches might maximise a boxer's punch force ability by implementing strength and conditioning programs that focus on increasing lower-limb strength without evoking mass gains, although this hypothesis needs to be explicitly tested in future research, or monitored on a case-by-case basis in each boxer. Possible training methods may include low volumes of high-load strength training of the lower limbs in a boxing-specific stance. In order to accurately advise training practise, future research should examine the effects of acute increases (e.g. due to warm-up strategies) or decreases (e.g. due to fatigue) in boxers' abilities to generate high levels of force in the lower body on their ability to produce peak punch force to determine whether such short-term alterations significantly impact punch force. Furthermore, future longitudinal research should examine the effect of strengthening the lower body on the ability to produce peak punch force in highly-trained boxers.

CHAPTER 6.

The effect of fatiguing lower-body exercise on punch impact forces in highly-trained boxers

6.1 Abstract

This study examined the effect of intense intermittent lower-body and trunk exercise (rowing) on punching performance in 28 highly-trained male amateur boxers. Straight- and bent-arm punch performances were assessed with a custom-built punch integrator using a 3-min maximal-effort punch test, completed in both non-fatigued (ROW_{pre}) and fatigued (ROW_{post}) states. A within-subject repeated measures design was implemented; participants completed ROW_{pre}, then 9 × 1-min bouts of rowing (1-min rest intervals), followed by ROW_{post}. Peak punch force and force-time variables, including impulse and rate of force development (RFD; calculated to five time points), were assessed. Differences between ROW_{pre} and ROW_{post} for each punch type (jab, cross, lead- and rear-hand hook) were tested with a linear mixed model, and effect sizes (Cohen's *d*) were calculated. Results showed significant ($p < 0.05$) reductions in punch force in ROW_{post} compared to ROW_{pre} for all punch types as well as significant delays in the time to reach specific force levels, and relative percentages of peak force (RFD) in all punches except the jab. It is likely that fatigue of the lower body and trunk muscles impaired ground reaction force, and thus punch force, production. This effect was larger in punches that involved a greater degree of trunk rotation, crosses and hooks, than in the jab which relies predominantly on arm extension. These findings reveal the negative effect of fatigue on punch force production, and provide evidence that lower-body and trunk force are important for generating punch force.

6.2 Introduction

The capacity to produce forceful punches that can negatively affect an opponent by way of bout domination or knockout is fundamental for boxing athletes [54, 61, 93]. Peak punch forces have been shown to be positively related to boxing expertise [6, 7, 64] and several studies have identified a positive relationship between punch force production and competition success [61, 70]. However, in addition to the technical and tactical ability to throw such punches, the physical capacity to produce the required levels of force is essential [22, 61]. In this respect, while several investigations have inferred that the ability to generate lower-limb muscle force is important, mechanisms contributing to punch force are not yet completely described.

Recent investigations of the physical attributes associated with punch force production have indicated that a key component is the capacity to produce high levels of force through the lower body (i.e. strength). Two recent studies (including Study 3 of this thesis) directly investigated the relationship between upper- and lower-body strength and power qualities and peak punch force in boxers [12]. In a sample of elite male and female boxers, Loturco et al. [12] found strong correlations between upper- and lower-body strength and power (measured in countermovement jump, squat and bench press tests) and peak punch force, and a significant difference between sexes in peak punch force capacity. Subsequently, in Study 3 of this thesis an all-male sample of highly-trained boxers was examined, and the ability to produce high levels of lower-body force (measured in isometric mid-thigh pull) and muscle power (countermovement jump tests) were found to be significantly associated with peak punch force production. It was also found that lower-body maximum isometric strength was found to be more closely related to punch force than power or rate of force development. These findings provide preliminary evidence that, in addition to technical expertise, the physical capacity of boxers is a key factor influencing punch force production, and highlights the idea that lower-body force production is an important factor in maximising it. In light of these recent findings, it is pertinent to more explicitly determine whether changes in lower-body strength influence punch force generation.

The intense physiological demands of elite amateur boxing are well documented. The activity-to-rest ratio has been reported as reaching 19.3:1 in elite male boxers [3], and high-intensity intermittent bursts of activity during a boxing bout have led to reports of blood lactate concentrations of 13.6 ± 2.4 $mmol \cdot L^{-1}$ [40], peak heart rates of 91.2 ± 4.3% of maximum, and oxygen uptakes equivalent to ~70% of peak oxygen consumption [42]. Furthermore, observational research of amateur boxing competition has inferred that fatigue may be present throughout a competitive bout, which is likely to have detrimental effects on boxing performance [24, 27, 74, 93]. One would expect that if lower-body force production was a key to successful punching performance, then the completion of lower-limb physical work bouts at intensities mirroring the physiological demands of boxing might result in a loss of punch force, even though the upper body (particularly the arm) remains unaffected. Such findings would not only reveal the implications for fatigue on a boxer’s punch capacity, but also provide secondary evidence for the importance of lower-limb force production to punching performance. The purpose of the present study was to examine the effect of a high-intensity bout of exercise targeting the lower body and trunk, on punching performance in highly trained male boxers. The hypothesis of the current study was that the capacity to produce force with the lower body would be impaired by fatigue and therefore punch force would be significantly impaired.

6.3 Methods

6.3.1 Study design and overview

A within-subject repeated measures design was used to assess the effect of an intense bout of lower-body exercise on punching performance in highly-trained amateur boxers. On a separate day prior to performance testing, the participants underwent a familiarisation session to gain experience with the prescribed testing and intervention protocols. During the familiarisation session participants completed one 3MTP trial in full and two 1-min maximal efforts trials on a rowing ergometer. The best rowing effort was used as a target to aim for during the intervention itself (described below).

6.3.2 Participants

Twenty-eight sub-elite male amateur boxers aged 19 ± 2 years (age range 16 - 24 years; height 177.3 ± 7.3 cm; body mass 70.5 ± 11.7 kg) volunteered for this study. Boxers attended an elite development athlete training camp with Boxing Australia at the Australian Institute of Sport, Canberra, Australia. All participants gave written informed consent before taking part in this study (or a parent/guardian provided informed consent for participants under 18 years) and were made aware that they could withdraw their data at any time. The study was approved by

Edith Cowan University Human Research Ethics Committee (ID: 12233) and all procedures were performed in accordance with the Declaration of Helsinki.

6.3.3 Procedures

Participants completed a standardised boxing-specific warm-up involving 5 min of aerobic activity in the form of steady-state rowing, followed by dynamic stretching, and bag punching at progressively increasing intensities (50%, 75%, 90%, 100% of maximal effort), before completing a 3-min punch test (3MPT; described in Study 2; Figure 4.1) as a boxing-specific performance test. The 3MPT is based on the previously reported activity rate of amateur boxing competition [3, 93] and includes short combinations of straight punches and bent arm punches completed at maximum intensity on a custom-built apparatus, the punch integrator (PI). Specifically, an audible beep and light flash triggers boxers to complete a short punch combination every 5 s for the duration of the test. The test contained three different punching combinations, which were performed within six 30-s cycles. The combination included: 1) five straight-arm punches (jab, cross, jab, cross, cross), 2) three lead-hand hooks, and 3) three rear-hand hooks. In order to execute lead- and rear-hand hooks, participants moved to a self-selected position on the appropriate side of the PI while maintaining their natural stance. Boxers completed combinations in the order 1, 2, 3, 1, 1 and then rested for 5 s, in each 30-s cycle; a total of 126 punches were thrown per test.

Punch force (newtons) was measured with the PI, which consisted of a wall-mounted S-beam load cell (KAC-E, Angewandte System Technik Gruppe, Germany) in series with the punch pad. The punch pad was set at the height of each participant's fist when their arm was extended horizontally. Using custom software and methods previously described in Study 2, the following variables were extracted or calculated from the punch integrator: impulse generated to the point of peak force (N·s; impulse), relative peak punch force ($N \cdot kg^{-1}$; relative punch force), time to 50% of peak force (ms; $t_{F50\%}$), time to 90% of peak force (ms; $t_{F90\%}$), time from 50% to 90% of peak force (ms; $t_{F50\text{-}90\%}$) time to 500 N (ms; t_{500N}), and force at 5 ms (N; F_{5ms}). Reliability and accuracy assessment of the PI and 3MPT (conducted in Study 2) indicate that after a single familiarisation session changes in punch force greater than 82 N, 80 N, 154 N, and 240 N for jab, cross, lead- and rear-hand hook punches, respectively (Table 4.3) can be detected and considered true. Typical error, CV, ICC, $SWC_{0.2}$, $SWC_{0.6}$ and $SWC_{1.2}$ for all variables and punches reported in the present study are listed in Table 4.3, Throughout all 3MPTs, heart rate (HR) was measured with a strap secured around the participant's chest (Polar

RS800, Kempele, Finland). Rating of perceived exertion (RPE; 6-20 a.u.; Borg, 1982) and blood lactate concentration ($[La^-]$) were measured (Lactate Pro II, Arkray, Japan) at the completion of the 3MPT. Participants completed the 3MPT twice in one session ~75 min apart (Figure 6.1); once in a rested state (ROW_{pre}) and once after an intense rowing protocol (ROW_{post}).

The rowing protocol was selected to induce significant muscle fatigue of the lower body and trunk. After considering the modes of exercise that were familiar to this cohort of boxers, rowing was selected as the preferred modality (in preference to, e.g. rope skipping or cycling) as it involves significant muscle activity of the hip and knee musculature as well as engaging the trunk muscles in both the stroke (dorsal/extensor muscles) and recovery (ventral/flexor muscles) phases [112-114], whereas skipping and cycling did not do this to the same extent. Additionally, the upper limb muscles used to generate force in rowing (i.e. elbow flexors; biceps brachii, brachioradialis [112, 115]) are different from those used to generate force in punching (i.e. push muscles; anterior deltoid, triceps brachii and pectoral muscles; [105]) The rowing protocol was completed after a 5-min steady-state warm-up bout on the rowing ergometer (Concept 2 Model D, Morrisville, USA) and required the completion of nine 1-min intense efforts on a rowing ergometer with a 1-min recovery period between. Participants were instructed to reach a target rowing distance that was equal to 90% of the distance they covered in a maximal effort trial during their familiarisation session, and were given verbal encouragement throughout. The mean peak HR and RPE throughout the protocol and $[La^-]$ after the ninth effort were 185 ± 11 bpm, 19 ± 2 a.u. and 11.2 ± 3.4 $mmol \cdot L^{-1}$, respectively, and the participants produced a mean power output across all efforts of 267 W, which was equivalent to 91% of their maximum 1-min effort. While the rowing protocol induced a similar physiological response to boxing competition (see data provided in Introduction for comparison) and relied predominantly on the trunk, hip and leg muscles, the upper-body muscles used for pushing were not heavily utilised and should not have been subsequently affected. All trials were conducted in thermoneutral conditions (23.6 ± 1.4 °C, 36.3 ± 4.3% relative humidity; 94.5 ± 0.2 kPa).

6.3.4 Statistical analysis

Data were analysed using IBM SPSS Statistical software (version 19). All data are expressed as mean ± SD. Performance results and physiological responses for the ROW_{pre} and ROW_{post} were compared using a linear mixed model with one level for test condition, alpha was set at *p*

< 0.05. Cohen's *d* was calculated to indicate the effect size (ES) of between-test differences and interpreted according Rhea's [83] scale for trained athletes in which < 0.25, 0.25 - 0.5, 0.50 - 1.0 and > 1.0 were termed trivial, small, moderate and large, respectively. To determine whether the magnitude of change could be interpreted as true, we compared the results of the present study to the TE and SWC determined in Study 2.

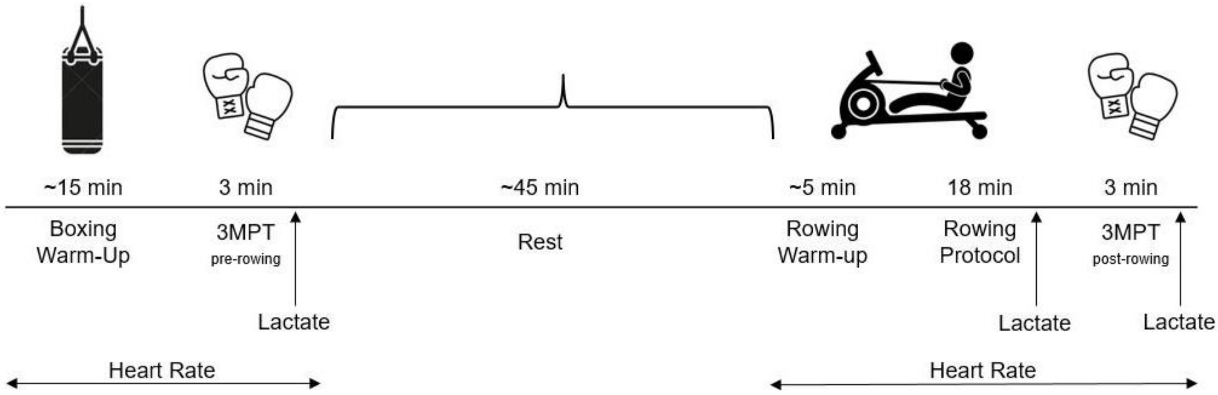

Figure 6.1. Schematic representation of the methods undertaken in Study 4. 3MPT = 3-min punch test; Lactate = measurement of blood lactate concentration; Heart Rate = continuous heart rate monitoring.

6.4 Results

Results of the ROW_{pre} and ROW_{post} are shown in Table 6.1, along with associated *p* values and effect sizes (*d*) for between-test differences. The majority of differences that were statistically significant were also of a greater magnitude than the TE reported in Study 2 (Table 4.3), with the exception of punch impulse, and punch force delivered in the jab, which generally changed within the range of measurement error. Physiological and perceptual responses to the ROW_{pre} and ROW_{post} are shown in Table 6.2. Peak HR and RPE were significantly higher in the ROW_{post} ($p = 0.013$; $p < 0.001$, respectively) compared to the ROW_{pre}. Average HR and [La$^-$] were higher in ROW_{post} compared to ROW_{pre} ($p = 0.002$; $p < 0.001$, respectively). Peak punch force decreased by 8.9% for the jab, 12.2% in the cross, 15.5% in the lead-hand hook, and 14.9% in the rear-hand hook. Time to reach relative percentages of peak force and specific levels of peak force ($t_{F50\%}$, $t_{F90\%}$, $t_{F50\text{-}90\%}$, and t_{500N}) were delayed by 1.6 - 5.6% for the jab, 1.4 - 13.1% for the cross, 4.7 - 16.7% for the lead-hand hook, and 6.9 - 16.5% for the rear-hand hook. Impulse and F_{5ms} were also reduced by 3.9 and 7.0% in the jab, 6.6 and 13.1% for the cross, 8.9 and 21.2% for the lead-hand hook, and 8.4 and 21.1% for the rear-hand hook, respectively.

Table 6.1. Overall and individual punch characteristics measured by the 3MPT in non-fatigued (ROW_{pre}) and fatigued (ROW_{post}) states.

		Peak force (N)	Relative force ($N \cdot kg^{-1}$)	Impulse ($N \cdot s$)	$t_{F50\%}$ (ms)	$t_{F90\%}$ (ms)	$t_{F50\text{-}90\%}$ (ms)	F_{5ms} (N)	t_{500N} (ms)
All	ROW_{pre}	1908 ± 384	27.0 ± 4.4	12.9 ± 2.1	7.1 ± 0.8	11.8 ± 1.1	4.7 ± 0.7	655 ± 127	4.9 ± 0.9
	ROW_{post}	1655 ± 344 *	23.4 ± 3.7 *	12.0 ± 2.1 *	7.4 ± 1.1 *	12.4 ± 1.4 *	5.1 ± 0.8 *	544 ± 99 *	5.5 ± 0.8 *
	p value	< 0.001	< 0.001	< 0.001	0.004	< 0.001	< 0.001	< 0.001	< 0.001
	Effect size (*d*)	0.69	0.90	0.42	0.27	0.53	0.54	0.97	0.62
Jab	ROW_{pre}	823 ± 271	11.5 ± 2.7	6.6 ± 2.2	7.2 ± 2.0	13.2 ± 3.0	6.0 ± 1.9	263 ± 97	7.7 ± 3.0
	ROW_{post}	753 ± 235 *	10.4 ± 2.3 *	6.4 ± 1.9	7.6 ± 3.3	14.0 ± 4.1	6.4 ± 2.0	247 ± 97 *	7.8 ± 3.3
	p value	0.001	< 0.001	> 0.05	> 0.05	> 0.05	> 0.05	0.020	> 0.05
	Effect size (*d*)	0.28	0.41	0.10	0.15	0.22	0.20	0.17	0.02
Cross	ROW_{pre}	1830 ± 387	26.0 ± 4.9	13.4 ± 2.8	7.6 ± 1.2	12.3 ± 1.6	4.7 ± 0.8	561 ± 120	5.1 ± 0.9
	ROW_{post}	1624 ± 397 *	22.9 ± 4.8 *	12.6 ± 3.0 *	7.7 ± 1.3	12.9 ± 1.7 *	5.1 ± 0.9 *	484 ± 108 *	5.7 ± 1.3 *
	p value	< 0.001	< 0.001	< 0.001	> 0.05	< 0.001	< 0.001	< 0.001	< 0.001
	Effect size (*d*)	0.53	0.63	0.27	0.13	0.35	0.50	0.67	0.56
Lead hook	ROW_{pre}	2491 ± 492	35.3 ± 5.6	15.1 ± 2.7	6.4 ± 1.0	10.3 ± 1.5	3.9 ± 0.8	949 ± 252	3.4 ± 0.6
	ROW_{post}	2089 ± 467 *	29.4 ± 5.3 *	13.7 ± 3.0 *	6.7 ± 1.0 *	11.1 ± 1.6 *	4.4 ± 1.1 *	751 ± 193 *	4.0 ± 0.7 *
	p value	< 0.001	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Effect size (*d*)	0.84	1.07	0.52	0.27	0.47	0.47	0.88	0.85
Rear hook	ROW_{pre}	2742 ± 571	38.8 ± 5.9	16.9 ± 2.8	6.6 ± 0.8	10.9 ± 1.1	4.3 ± 0.7	1016 ± 228	3.2 ± 0.5
	ROW_{post}	2337 ± 520 *	32.9 ± 5.4 *	15.5 ± 2.7 *	7.1 ± 0.9 *	11.8 ± 1.3 *	4.7 ± 1.05 *	808 ± 165 *	3.7 ± 0.5 *
	p value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Effect size (*d*)	0.74	1.04	0.53	0.51	0.71	0.44	1.04	0.94

Values are expressed as mean ± SD; * = significantly different to rested condition ($p < 0.05$), *p* value only specified if significant.

Table 6.2. Physiological and perceptual responses to 3MPT in non-fatigued (ROW_{pre}) and fatigued (ROW_{post}) states.

	ROW_{pre}	ROW_{post}
Peak heart rate (bpm)	168 ± 9	176 ± 14
Average heart rate (bpm)	150 ± 10	160 ± 13
RPE 6-20 scale (a.u.)	14 ± 2	18 ± 1 *
$[La^-]$ ($mmol·L^{-1}$)	3.0 ± 0.6	10.7 ± 2.9 *

Values are expressed as mean ± SD; * = significantly ($p < 0.05$) different from pre-rowing 3MPT.

6.5 Discussion

Successful amateur boxers require the ability to punch with high impact forces, even towards the end of a high-intensity bout. In the present study, the effect of intense intermittent lower-body and trunk exercise (rowing) on punching performance in highly-trained amateur boxers was examined. The main findings were that the intense repeated bouts of rowing exercise significantly affected boxers' capacities to punch forcefully. This effect was greatest for punches with movement patterns that utilise trunk rotation and leg drive, including the lead- and rear-hand hooks and crosses, and lesser for the jab, which requires a mostly linear hand trajectory in the sagittal plane and relies less on trunk rotation. The loss of punch force can be predominantly explained by the fatigue induced in the lower limb and trunk punches caused by the rowing exercises; these muscles must therefore be important for force production in rear-hand straight punches and hooks.

In the cross and hooks from the lead and rear hands, there were significant performance reductions for all variables relating to force, impulse and rate of force development, with the exception of $t_{F50\%}$ for the cross (see Table 6.1). Moreover, the time to reach relative percentages of peak force and fixed time markers of force exertion were all delayed in the ROW_{post}. These results indicate that the rowing protocol reduced the amount of impact force the boxers were able to generate as well as changing the RFD profile, with punch impact being exerted over a longer duration while also producing a smaller net impulse (e.g. Figure 6.2). These results are likely to be related to the kinematics of the cross and hooks. For the cross, or rear-hand straight punch, the trajectory of the arm is mostly sagittal, which results in linear acceleration of a target after impact, however there is a large rotational component in the trunk [65, 70] and large contribution from the lower limb musculature [4]. The same is true of lead- and rear-hand hook movement patterns, with the key difference being the arcing arm trajectory resulting in high rotational accelerations delivered to the side of the target [68]. Given that the high-intensity rowing protocol completed by the participants would have required a large production of muscular force from the legs and trunk [114] it is very likely that the muscle recruitment and coordination patterns necessary for high impact punching were subsequently negatively affected. The effect of rowing on performance of these punch types is likely to be two-fold, given the importance of lower-limb force production in punching [4]. First, during the ROW_{post} it is unlikely that participants were able to generate the force required through ground reaction forces to transfer through the kinetic chain and into the punch when leg muscle force production was compromised. Second, given that the impulse required to create functional punch impact and the time required for punch force production (e.g. $t_{F90\%}$, $t_{F50-90\%}$, t_{500N}) were also negatively affected it is likely that the trunk muscles were fatigued such that boxers were less able to utilise trunk rotation during punch execution. Both of these effects may have contributed to the loss of punch force. Future research in which ground reaction forces and joint kinematics are measured would provide an explicit check on these assumptions.

In contrast, the punch force in the jab was less affected by the rowing exercises. Although punch force relative to body mass, and F_{5ms} were significantly reduced, the ES of these differences were classified as small [83] and were much smaller than the other punches analysed (7 - 9% vs. 12 - 21%). Moreover, the magnitude of change detected in the jab was less than the typical error established in Study 2, and thus change may have been a result of measurement error rather than the rowing intervention. Furthermore, punch impulse and the force produced at specific time points in the jab were unchanged after the bout of rowing, indicating that the fatiguing exercise had a lesser effect on the jab compared to the other punches. Impact forces produced by the jab were much lower than in the crosses and hooks (Table 6.1 and Figure 6.2), which is consistent with previous findings [5, 7, 12] and the findings from Study 2. Further, the jabs may be used as a tactical punch to create an opportunity for a powerful cross or hook to be delivered [65] and even though the participants were given instructions to punch as hard and fast as possible, jabs might have been subconsciously delivered with submaximal force in preparation for a subsequent technique. From a biomechanical perspective, the jab requires acceleration of the arm over a short distance predominantly in the sagittal plane and mainly relies on elbow extension to exert linear forces to the opponent. The lower impact forces compared to other punches have been attributed to a smaller contribution of force from the legs [64], limited trunk rotation, and a shorter distance over which the arm is accelerated [67]. Indeed, the smaller punch force requires less forward momentum prior to punch initiation, which in turn ensures that a smaller ground reaction force is needed and subsequently a lesser force production by the lower body musculature.

Accordingly, lower-body and trunk muscle fatigue induced by the intense rowing exercise is expected to have a smaller effect on the jab [112-114].

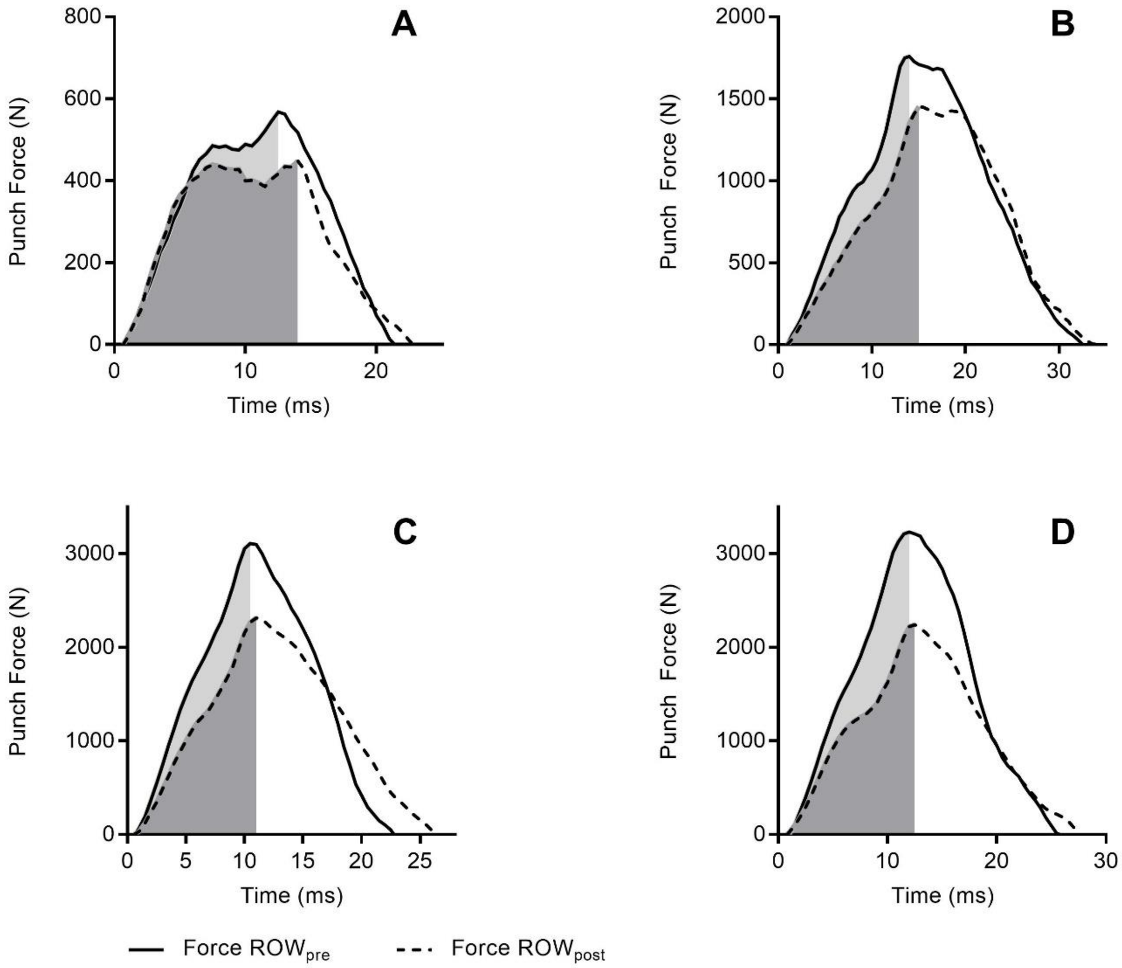

Figure 6.2. Example force data for force production during the 3-min punch test (3MPT). Panel (A) jab, (B) cross, (C) lead-hand hook and (D) rear-hand hook, delivered in a non-fatigued (ROW_{pre}) and fatigued (ROW_{post}) state. Light shading = pre-rowing impulse, dark shading = post-rowing impulse.

The prescribed rowing exercise induced a significant amount of fatigue (HR = 185 bpm, RPE = 19 a.u., [La^-] = 11.2 mmol·L^{-1}) which was sufficient to negatively impact punching performance, although it remains to be seen if this effect is comparable to an intense bout of boxing. In any case, the physiological and perceptual responses recorded in the ROW_{post} and throughout the rowing exercise are comparable to the range of results reported in previous investigations in boxing. The present results for HR and [La^-] in the ROW_{post} and rowing protocols are similar to peak heart rate responses (187 - 191 bpm; [11, 41]) and blood lactate concentrations (8.9 - 13.6 mmol·L^{-1}; [11, 40, 41]) in unofficial or simulated competition boxing bouts. These physiological responses in addition to the increases in RPE to near maximum (19 a.u. - extremely hard), indicate that the physiological and perceptual responses to the rowing protocol were comparable to the high-intensity demands of competitive boxing. A key difference was that rowing predominantly utilised the arm flexor muscles [112, 115] and should have induced minimal fatigue in arm extensor muscles, thus maintaining the capacity to provide significant arm extension forces. Of course, it remains to be determined whether performance decrements seen in the present study are similar to the performance decrements that might be elicited during competitive boxing bouts; future research should seek to investigate this further.

In summary, intense rowing exercise, which required substantial force production of the lower body and trunk musculature without significant activity from the arm extensor muscles [112, 115], had a significant detrimental effect on punching performance. In complex rear-hand straight and hook punches, the muscular fatigue induced by the rowing exercise would likely have affected ground reaction force production and trunk rotation, which have previously been shown to be important for the forceful execution of these punches. In punches with less complex movement patterns such as the jab, the exercise had less effect, probably because a lower total force production is necessary and a greater proportion of this force is produced by arm extension muscles. Since the level of fatigue induced by rowing exercise is comparable to the level of fatigue induced by boxing competition there is the potential that the fatigue in boxing might cause a comparable reduction in punch force. However, since boxing exercise is qualitatively different, this hypothesis remains to be explicitly tested in future research. Furthermore, this study is limited by the fact that there was no control condition for comparison, and thus future research comparing rowing to boxing activity should also include a non-exercise control. Regardless, training methods that induce acute or chronic reductions in lower-limb and trunk muscle force capacity might be expected to decrease punch force and, speculatively, training methods that increase lower-limb and trunk force capacity might be expected to increase punch force; future research should investigate these speculations. Furthermore, conditioning practices that allow boxers to perform under fatiguing conditions may be advantageous in the preparation of boxers for high-intensity, potentially fatiguing bouts. Nonetheless, boxers might be counselled to avoid fatiguing lower-body exercise (such as rowing) before boxing-specific muscle power training sessions to ensure the quality of the sport-specific session. In a practical sense, the jab may serve as an advantageous tool for boxers under fatiguing conditions, given the lesser requirement for whole-body force production.

CHAPTER 7.

The effect of competitive boxing versus non-boxing fatiguing exercise on punch impact forces in highly-trained amateur boxers

7.1 Abstract

This study examined the effect of a competitive boxing bout versus high-intensity but non-specific fatiguing muscular activity (rowing) on the ability to produce punch force in 20 highly-trained male amateur boxers. Punch performance was assessed using a 3-min maximal-effort punch test, completed twice (pre- and post-intervention) in three conditions: rowing (ROW; 9 × 1-min bouts of rowing with 1 min rests), boxing (BOX; a competitive boxing bout), and a non-exercise control (CON; 75 min rest). Peak punch force, impulse and rate of force development (RFD; calculated to five time points) were assessed. A single cohort, crossover design with repeated measures was implemented. The effects and magnitudes of change according to condition and test time (pre- vs. post-intervention) on punch force and physiological variables were quantified using a linear mixed model with two levels (condition and test). Alpha was set at 0.05, and effect sizes (Cohen's *d*) and 95% confidence intervals (95% CI) were calculated. Results showed significant ($p < 0.05$) punch force reductions from ROW_{pre} to ROW_{post} in jab and lead-hand hook punches. However, no significant changes were observed in CON or BOX, and RFD variables and impulse remained unchanged in all conditions. Reductions in punch performance after rowing most likely resulted from fatigue accumulated in the lower body and trunk muscles, which are important for producing punch force, whereas muscular fatigue during boxing is likely to have accumulated in areas that had less influence on punch force production. In contrast to the near-maximal effort required in ROW intervention, participants were able to freely regulate workload in BOX, which may have allowed them to minimise fatigue accumulation and maintain punch force. These findings suggest that boxers are able to maintain punch force production throughout a boxing bout, and pacing during the bout may partly explain this punch force maintenance.

7.2 Introduction

Amateur boxing competition involves combatants attempting to strike their opponent while avoiding being punched in return [27]. Currently, amateur boxing bouts are officiated using the Ten Point Must-System (TPMS), in which judges decide a winner according to their perceptions of technical and tactical superiority, dominance and competitiveness [2]. Delivering a punch with high impact force has been shown to be an important factor in achieving success during a bout [5, 61]. Indeed, either a single punch with sufficient force to knockout the opponent or persistent damaging punches, which can establish dominance over the opponent, are associated with winning a competitive bout [61, 93]. A boxer's skill level and technique are undoubtedly crucial in delivering a forceful punch to an opponent. Previous research highlights that level of expertise is a key differentiator when it comes to punch force application [7, 64]. Physical strength attributes are also important. For example, it has been established (in Study 3) that lower-body muscular strength and power are strongly associated with peak punch force [4, 12]. Greater leg strength in particular is thought to contribute to the production of a greater ground reaction force, which is needed to create forward momentum that is transferred through the trunk and arm, resulting in a greater punch impact force [19]. One recent study (Study 4) showed that a fatigue-induced decrease in force production capacity in lower body and trunk musculature was associated with a decrease in peak punch force, punch impulse, and punch RFD in highly-trained amateur boxers. However, it has not yet been established whether the level of fatigue experienced by boxers during a competition bout affects punch force.

The intense physiological demands of competition boxing have been well researched [22, 40, 42]. Boxers must be able to maintain activity-to-rest ratios of up to 19.3:1 for the 9-min duration of a competitive amateur bout; thus, experiencing some level of fatigue during a bout is expected [3]. Given the metabolic similarities between combat sports and rowing exercise [116, 117], high-intensity interval training utilising rowing exercises has been implemented in the physical conditioning programming of combat sport athletes [118, 119]. Recent findings (Study 4 of this thesis) have shown that an intense bout of intermittent rowing activity, which targets the lower-limb and trunk muscles [112-114], compromises subsequent punch force production (peak force, rate of force application and impulse). In that study, the fatiguing rowing exercise negatively affected punches that benefit from the production of force by the lower body and trunk musculature (i.e. the rear-hand straight punch and hooks thrown with the lead and rear hands) to a greater extent than those that do not, such as the jab [65, 67]. While these findings highlight the important contributions of the lower body and trunk musculature in producing punch force, it still remains to be seen whether the performance decrements observed are relevant to boxing where fatigue is induced predominantly through actions such as clinching, punching and non-punching body movements (e.g. stepping and bouncing around the ring), in addition to the impact of the opponents punches on the boxer's body.

The high-intensity, intermittent work bouts that are characteristic of amateur boxing mean that combatants are likely to experience fatigue during both training and competition [1]. The technical and behavioural aspects of elite amateur boxing bouts have been reported previously (including in Study 1 of this thesis), and data in those studies is suggestive that boxers experience various levels of fatigue throughout a competitive bout [22, 93]. This fatigue can manifest as technical changes, such as alterations in the number of punches thrown in combination (i.e. repetitively), the selective use of defensive actions, or behavioural changes such as adoption of a 'translational' movement style (becoming flat footed and bouncing less) and intermittently dropping the arms (i.e. dropping the guard [93]). Under the TPMS, these changes may influence the judges' perceptions of bout dominance [22, 24, 54]. In addition, previous research has suggested that the negative effects of fatigue on punch force production may impede a boxer's ability to show dominance, or negatively affect the opponent during a competitive boxing bout (Study 4), as high punch force has been associated with success in boxing competition [61]. However, the effects of boxing-induced fatigue on punch force production have not been examined. It may be hypothesised that whole-body fatigue (shown by changes in heart rate, blood lactate concentration and rating of perceived exertion) induced by rowing, that is physiologically similar to the levels previously observed during boxing competition, may impose a similar threat to punch force production. Therefore, the aim of the present study was to examine and compare the effects of competitive boxing and high-intensity lower-limb and trunk muscle fatigue (rowing) on punch performance in highly-trained boxers.

7.3 Methods

7.3.1 Participants

Twenty highly-trained male amateur boxers aged 18 ± 2 years (age range 16 - 24 years; height, 173.6 ± 8.8 cm; body mass, 67.7 ± 13.6 kg) volunteered to participate in this study while attending a high performance training camp at the Australian Institute of Sport Combat Centre

(Canberra, Australia). Boxers were number one or two in the nation for their respective age and weight categories. Voluntary informed consent was obtained from all participants before taking part in this study and all participants were made aware that they could withdraw their data from the study at any time. Participants under the age of 18 years had a parent or guardian provide written informed consent on their behalf. The study was conducted in accordance with the Declaration of Helsinki and approved by Edith Cowan University Human Research Ethics Committee (ID: 12233).

7.3.2 Procedures

A single cohort, crossover design with repeated measures was implemented. Participants completed a familiarisation session prior to official testing in which they were taught the punch performance protocol (see below) and, when comfortable, then completed it in full at maximum intensity within the same session. On official testing days, they completed the punch performance test then subsequently completed either a passive rest period lasting approximately 75 min (CON), an intense bout of intermittent rowing exercise (ROW), or a competitive boxing bout (BOX), before completing the punch performance test a second time. Participants completed a standardised, 20-min, boxing-specific warm-up before punch testing commenced. The warm-up included 5 min of steady-state rowing, dynamic stretches and punching a punching bag at increasing intensities. Participants were given 5 min to complete any additional warm-up activities and put on 10-ounce testing gloves before the punch assessment began. Punch performance was assessed with the 3-min punch test (3MPT) on a punch measurement apparatus (the punch integrator; described in Study 2). The 3MPT includes short combinations of straight and bent arm punches completed at maximum intensity. Participants completed the 3MPT before and after undertaking activity under three conditions: control (CON_{pre} and CON_{post}), rowing (ROW_{pre} and ROW_{post}) and boxing (BOX_{pre} and BOX_{post}), described below. The punch integrator, used to measure punch force (newtons), was comprised of a wall-mounted S-beam load cell (KAC-E, Angewandte System Technik Gruppe, Germany) in series with the punch pad. The punch pad was individually set at the height of each participant's fist when their arm was extended horizontally. Variables that were extracted or calculated using previously described methods (in Study 2) from the punch integrator included: peak punch force (N), peak punch force relative to body mass ($N \cdot kg^{-1}$; relative punch force), impulse generated to the point of peak force (N·s; impulse), force at 5 ms (N; F_{5ms}), time to 500 N (ms; t_{500N}), time to 50% of peak force (ms; $t_{F50\%}$), time to 90% of peak force (ms; $t_{F90\%}$) and time from 50% to 90% of peak force (ms; $t_{F50\text{-}90\%}$). These variables were identified amongst a larger set of variables to describe punch impact force production with minimal information replication (i.e. reduced inter-correlation) and good reliability (Study 2). An average of each punch type thrown throughout each test was taken for analysis (i.e. jab, cross, lead-hand hook, and rear-hand hook) as well as an average of all punches. Heart rate (HR) was measured with a strap secured around the participant's chest (Polar RS800, Kempele, Finland) throughout all 3MPTs, and blood lactate concentration ([La^-]; Lactate Pro II, Arkray, Japan) as well as rating of perceived exertion (RPE; 6-20 a.u.; [94]) were measured and recorded at the completion of the 3MPT. All trials were conducted in thermoneutral conditions (23.2 ± 1.1 °C, 48.5 ± 3.2% relative humidity; 126.7 ± 0.4 kPa).

7.3.2.1 Control condition (CON)

All participants (n = 20) completed the 3MPT twice, separated by approximately 75 min. During this rest period participants were free to move about the room but no physical activity was undertaken until the warm-up for the post-intervention test commenced.

7.3.2.2 Rowing condition (ROW)

A fatiguing rowing ergometer protocol, outlined in Study 4, was implemented to induce fatigue of the lower body and trunk muscles [112-114] and arm flexors [112, 115], while having minimal effect on the muscles of the upper body that are used for punching (the arm extensors i.e. triceps brachii, anterior deltoid, and pectoral muscles [105]). During the familiarisation session, all participants completed two 1-min maximal efforts on a rowing ergometer (Concept 2 Model D, Morrisville, USA) after the 3MPT. The best 1-min maximal performance was used on the testing day as a target to aim for during the intervention. On testing days, the rowing protocol was completed after a 5-min steady-state warm-up bout on the rowing ergometer and involved boxers completing nine 1-min intense efforts with a 1-min recovery period between. Participants were instructed to reach 90% of the distance they covered in the single maximal effort trial during their familiarisation session in each effort of the rowing protocol. Participants were given strong verbal encouragement throughout the rowing protocol. The rowing protocol elicited physiological responses such that the participant's peak HR and RPE throughout the protocol were 191 ± 2 bpm, 20 ± 0 a.u., respectively, and [La^-] after the ninth effort was 10.5 ± 2.5 $mmol \cdot L^{-1}$. On average the participants achieved power outputs equivalent to 92% (262 W) of the maximum effort obtained in familiarisation. All participants completed the rowing condition (n = 20).

7.3.2.3 Boxing condition (BOX)

Participants competed in a simulated competition sparring bout against an opponent of similar mass and skill (as determined by a panel of elite coaches). The bouts were held in a 3 × 3-min format and conducted in accordance with AIBA rules and regulations [2]. Bouts were judged with the TPMS, and the winner was offered an incentive. The winner was always announced after the post-bout 3MPT was completed in order to minimise possible effects on motivation before the post-intervention 3MPT. Peak HR throughout the bout and post-bout [La^-] (i.e. measured at the conclusion of the final round) were 193 ± 9 bpm, and 7.9 ± 3.4 mmol·L^{-1} respectively, and were statistically similar (determined by a paired-sample t-test with two tails; $p > 0.05$) to the physiological responses of the rowing protocol. Rating of perceived exertion response to BOX was 16 ± 3 a.u., and was significantly lower than ROW ($p = 0.022$). Given that the participants were matched with opponents of similar size (weight category) and ability, additional boxers who were not participating in the study were recruited to fight against the participating boxers. However, to ensure boxers were properly matched, many participants also served as each other's opponent and, in order for the time between the conclusion of the competitive bout and the start of the 3MPT to remain consistent, only one boxer per bout could be tested within the appropriate timeframe. As a result, a total of 11 participants, who were chosen by the coaches of the camp, completed the 3MPT trials before and after the BOX intervention (n = 11). While this is a limitation, the physical characteristics (i.e. height, body mass and age) and the punch force capacity of the boxers chosen to complete the BOX intervention did not differ from sample that completed CON and ROW conditions.

7.3.3 Statistical analysis

Data were analysed using IBM SPSS Statistics (version 19) and all data are expressed as mean ± SD. A linear mixed model with two levels for condition and test (and condition × test interactions) was used to assess between-test and between-condition differences for all punch variables and physiological data collected during the 3MPT assessments; alpha was set at 0.05. This statistical approach was used as it allows the comparison of uneven group sizes (i.e. n = 20 for CON and ROW and n = 11 for BOX) [120]. Where significant effects were observed, Fisher's Least Significant Difference [109] correction was applied to post-hoc analyses to identify where differences occurred. Effect sizes (Cohen's *d*) and 95% confidence intervals (95% CI) were calculated for differences between tests of the same condition (pre- vs. post-intervention tests, e.g. CON_{pre} vs. CON_{post}). Effect size magnitudes were classified using the scale advocated by Rhea [83] for trained athletes in which < 0.25, 0.25 - 0.5, 0.50 - 1.0 and >

1.0 were termed trivial, small, moderate and large, respectively. The percentage change (Δ%) for differences between pre- and post-intervention tests was calculated for punch performance variables in each condition [$\Delta\% = \frac{post-pre}{pre} \times 100$]. Between-day reliability was assessed by calculating typical error (TE), coefficient of variation (CV) and interclass correlation coefficient ($ICC_{3,1}$; two-way mixed, single measure) [95, 96] for the first test completed on each testing day (i.e. CON_{pre}, ROW_{pre} and BOX_{pre}).

7.4 Results

Results of the between-day reliability analyses for CON_{pre}, ROW_{pre} and BOX_{pre} revealed good reliability for most punch performance variables in most punch types. Specifically, performance variables for jabs had ICCs of 0.759 - 0.960 and CVs of 5.7 - 8.4%, with the exception of t_{500N} (17.5%), F_{5ms} (17.5%) and $t_{F90\%}$ (11.2%). The CVs for crosses were 4.2 - 10.5% with ICCs of 0.727 - 0.891. Similarly lead-hand hooks had CVs of 2.9 - 9.5% and ICCs of 0.814 - 0.953, although rear-hand hooks were less consistent with CVs of 5.0 - 16.2% and ICCs of 0.614 - 0.873).

Results of the punch performance testing for CON, ROW and BOX conditions are shown in Table 7.1 and Figure 7.1. The linear mixed model and post-hoc analyses revealed that peak punch force and punch force relative to body mass were significantly reduced in ROW_{post} for the jab (both $p = 0.002$) and lead-hand hook ($p = 0.009$ and $p = 0.015$, respectively) as well as F_{5ms} in the lead-hand hook ($p = 0.013$) when compared to ROW_{pre}. In addition, there were significant differences in cross t_{500N} ($p = 0.024$) and lead-hand hook peak force ($p = 0.049$) and punch force relative to body mass ($p = 0.037$) between CON_{pre} and BOX_{pre}. Effect sizes and classifications [83] for the differences between pre- and post-intervention tests in each condition are shown in Table 7.2. as well as the percentage change (Δ%) for all variables between the pre- and post-intervention tests in each condition (e.g. CON_{pre} vs. CON_{post}).

Physiological and perceptual responses in all tests from all conditions are shown in Table 7.1. ROW_{post} and BOX_{post} showed significantly higher average HR ($p = 0.001$ and $p = 0.004$, respectively), RPE ($p < 0.001$ and $p < 0.001$, respectively) and [La^-] ($p < 0.001$ and $p < 0.001$, respectively) than ROW_{pre} and BOX_{pre}, respectively, but no significant difference ($p > 0.05$) in physiological responses to 3MPT were observed between CON_{pre} and CON_{post}. Effect sizes and classifications for physiological responses to 3MPT in all conditions are shown in Table 7.2.

Table 7.1. Punch force characteristics measured by the 3MPT in three pre- and post-intervention conditions.

		Control (CON)		Rowing (ROW)		Boxing (BOX)	
		CON_{pre}	CON_{post}	ROW_{pre}	ROW_{post}	BOX_{pre}	BOX_{post}
Jab	Peak force (N)	840 ± 203	843 ± 201	856 ± 217	786 ± 185 *	791 ± 190	764 ± 185
	Relative force ($N \cdot kg^{-1}$)	12.5 ± 2.4	12.5 ± 2.2	12.7 ± 2.2	11.7 ± 2.4 *	11.2 ± 1.9	10.9 ± 1.9
	Impulse (N·s)	6.4 ± 1.8	6.6 ± 1.7	6.4 ± 1.9	6.1 ± 1.5	6.2 ± 1.4	6.0 ± 1.1
	$t_{F50\%}$ (ms)	7.6 ± 3.2	7.5 ± 2.3	7.1 ± 2.4	7.9 ± 4.2	9.2 ± 4.3	9.6 ± 5.6
	$t_{F90\%}$ (ms)	12.2 ± 3.7	12.1 ± 2.7	11.5 ± 2.7	12.7 ± 4.8	14.1 ± 4.7	14.5 ± 5.9
	$t_{F50\text{-}90\%}$ (ms)	4.6 ± 0.6	4.7 ± 0.6	4.5 ± 0.6	4.8 ± 0.9	4.9 ± 0.6	4.9 ± 0.7
	t_{500N} (ms)	7.5 ± 2.1	8.0 ± 1.9	7.7 ± 2.2	8.3 ± 3.3	9.5 ± 4.7	10.3 ± 5.5
	F_{5ms} (N)	283 ± 127	273 ± 121	296 ± 122	269 ± 126	231 ± 135	220 ± 131
Cross	Peak force (N)	1863 ± 314	1802 ± 289	1842 ± 297	1682 ± 330	1687 ± 343	1605 ± 288
	Relative force ($N \cdot kg^{-1}$)	28.5 ± 7.4	27.4 ± 6.4	28.1 ± 6.8	25.7 ± 7.0	24.5 ± 5.6	23.4 ± 5.1
	Impulse (N·s)	14.6 ± 2.7	14.4 ± 2.5	14.1 ± 2.8	13.8 ± 3.4	13.4 ± 3.4	12.9 ± 2.9
	$t_{F50\%}$ (ms)	6.9 ± 1.0	6.9 ± 1.1	6.8 ± 0.8	6.9 ± 1.1	7.4 ± 1.7	7.3 ± 1.3
	$t_{F90\%}$ (ms)	11.4 ± 1.4	11.7 ± 1.5	11.2 ± 1.2	11.6 ± 1.4	11.9 ± 1.9	11.9 ± 1.5
	$t_{F50\text{-}90\%}$ (ms)	4.6 ± 0.8	4.7 ± 0.9	4.4 ± 0.5	4.7 ± 0.5	4.5 ± 0.4	4.5 ± 0.4
	t_{500N} (ms)	4.7 ± 1.1	4.9 ± 1.2	4.7 ± 1.1	5.1 ± 1.4	5.6 ± 1.7 ǂ	5.7 ± 1.4
	F_{5ms} (N)	621 ± 152	593 ± 142	615 ± 139	558 ± 145	526 ± 152	497 ± 139
Lead hook	Peak force (N)	2424 ± 381	2300 ± 362	2410 ± 327	2090 ± 289 *	2287 ± 427 ǂ	2209 ± 351
	Relative force ($N \cdot kg^{-1}$)	36.7 ± 7.0	34.7 ± 6.0	36.4 ± 6.2	31.8 ± 6.8 *	32.9 ± 5.7 ǂ	31.8 ± 4.9
	Impulse (N·s)	14.9 ± 2.4	14.5 ± 2.5	14.7 ± 2.3	13.9 ± 2.3	14.5 ± 2.6	14.4 ± 2.8
	$t_{F50\%}$ (ms)	5.9 ± 0.7	6.0 ± 0.8	5.8 ± 0.7	6.0 ± 0.9	6.0 ± 1.0	6.2 ± 1.0
	$t_{F90\%}$ (ms)	9.4 ± 1.0	9.6 ± 1.2	9.4 ± 1.0	9.9 ± 1.3	9.7 ± 1.4	10.0 ± 1.4
	$t_{F50\text{-}90\%}$ (ms)	3.6 ± 0.4	3.7 ± 0.5	3.6 ± 0.4	3.9 ± 0.5	3.7 ± 0.5	3.8 ± 0.4
	t_{500N} (ms)	3.4 ± 0.5	3.5 ± 0.4	3.3 ± 0.4	3.8 ± 0.6	3.6 ± 0.7	3.8 ± 0.6
	F_{5ms} (N)	977 ± 194	910 ± 172	995 ± 178	823 ± 203 *	909 ± 259	835 ± 214
Rear hook	Peak force (N)	2526 ± 446	2459 ± 517	2536 ± 371	2309 ± 445	2548 ± 671	2424 ± 518
	Relative force ($N \cdot kg^{-1}$)	38.7 ± 6.7	36.7 ± 5.9	38.3 ± 6.5	34.9 ± 7.4	36.7 ± 8.4	35.1 ± 7.6
	Impulse (N·s)	16.2 ± 2.7	15.8 ± 3.0	16.0 ± 2.4	15.5 ± 2.6	16.2 ± 3.1	16.0 ± 2.4
	$t_{F50\%}$ (ms)	6.1 ± 0.8	6.2 ± 0.9	6.1 ± 0.9	6.3 ± 0.9	6.4 ± 1.0	6.7 ± 1.2
	$t_{F90\%}$ (ms)	10.1 ± 1.1	10.3 ± 1.1	10.1 ± 1.4	10.5 ± 1.3	10.4 ± 1.2	11.1 ± 1.5
	$t_{F50\text{-}90\%}$ (ms)	4.0 ± 0.4	4.1 ± 0.5	4.0 ± 0.6	4.2 ± 0.6	4.0 ± 0.5	4.4 ± 0.5
	t_{500N} (ms)	3.3 ± 0.5	3.4 ± 0.5	3.3 ± 0.5	3.6 ± 0.5	3.5 ± 0.8	3.7 ± 0.9
	F_{5ms} (N)	995 ± 223	939 ± 212	991 ± 215	867 ± 208	926 ± 288	849 ± 269
Physiological response	Average HR (bpm)	152 ± 11	151 ± 12	154 ± 12	165 ± 13 *	151 ± 13	164 ± 12 *
	Peak HR (bpm)	166 ± 13	164 ± 13	170 ± 21	176 ± 13	169 ± 10	180 ± 13
	RPE (a.u.)	15 ± 2	14 ± 4	14 ± 2	17 ± 20 *	13 ± 2	17 ± 3 *
	$[La^-]$ ($mmol \cdot L^{-1}$)	3.1 ± 0.9	2.6 ± 1.0	3.1 ± 1.3	10.0 ± 2.6 *	2.5 ± 0.7	8.0 ± 3.3 *

Table 7.1. Results for the pre- and post-intervention 3MPT under a control (CON), rowing (ROW) and boxing (BOX) conditions. Values are expressed as mean ± SD; * = significantly ($p < 0.05$) different from the pre-intervention result in the same condition; ǂ = significantly ($p < 0.05$) different from CON_{pre}.

Table 7.2. Differences between pre- and post-intervention 3MPT in three test conditions.

		Control (CON)			Rowing (ROW)			Boxing (BOX)		
		Δ%	Effect size (95% CI)	Effect size classification	Δ%	Effect size (95% CI)	Effect size classification	Δ%	Effect size (95% CI)	Effect size classification
Jab	Peak force (N)	0.5 ± 4.0	-0.01 (-0.63 - 0.61)	Trivial	-7.8 ± 7.3	0.37 (-0.26 - 0.99)	Small	-1.9 ± 8.4	0.14 (-0.70 - 0.97)	Trivial
	Relative force (N·kg^{-1})	2.7 ± 7.4	-0.01 (-0.63 - 0.61)	Trivial	-1.5 ± 15.2	0.51 (-0.12 - 1.14)	Moderate	0.1 ± 5.4	0.18 (-0.66 - 1.01)	Trivial
	Impulse (N·s)	1.8 ± 9.4	-0.08 (-0.70 - 0.54)	Trivial	8.4 ± 17.7	0.18 (-0.45 - 0.80)	Trivial	2.6 ± 11.3	0.16 (-0.67 - 1.00)	Trivial
	$t_{F50\%}$ (ms)	1.5 ± 10.0	0.03 (-0.59 - 0.65)	Trivial	8.6 ± 18.2	-0.17 (-0.79 - 0.46)	Trivial	2.2 ± 13.1	-0.07 (-0.91 - 0.76)	Trivial
	$t_{F90\%}$ (ms)	2.1 ± 13.6	0.01 (-0.61 - 0.63)	Trivial	15.1 ± 30.2	-0.22 (-0.84 - 0.40)	Trivial	4.7 ± 22.4	-0.08 (-0.91 - 0.76)	Trivial
	$t_{F50\text{-}90\%}$ (ms)	1.8 ± 10.1	0.22 (-0.40 - 0.85)	Small	8.0 ± 15.8	-0.46 (-1.09 - 0.17)	Small	1.0 ± 6.8	-0.08 (-0.91 - 0.76)	Trivial
	t_{500N} (ms)	-1.6 ± 15.8	-0.24 (-0.86 - 0.39)	Small	-13.1 ± 19.1	-0.10 (-0.72 - 0.52)	Trivial	-0.9 ± 33.2	-0.15 (-0.99 - 0.69)	Trivial
	F_{5ms} (N)	1.8 ± 21.2	0.08 (-0.54 - 0.70)	Trivial	-14.9 ± 20.5	0.20 (-0.42 - 0.82)	Trivial	-3.0 ± 34.3	0.08 (-0.76 - 0.91)	Trivial
Cross	Peak force (N)	-2.9 ± 8.5	-0.01 (-0.63 - 0.61)	Trivial	-9.0 ± 6.7	0.20 (-0.42 - 0.82)	Trivial	-1.1 ± 13.4	0.25 (-0.59 - 1.09)	Trivial
	Relative force (N·kg^{-1})	-2.9 ± 8.5	-0.01 (-0.63 - 0.61)	Trivial	-9.0 ± 6.7	0.15 (-0.47 - 0.77)	Trivial	-1.1 ± 13.5	0.21 (-0.63 - 1.05)	Trivial
	Impulse (N·s)	-0.6 ± 8.7	-0.08 (-0.70 - 0.54)	Trivial	-2.6 ± 10.6	0.06 (-0.56 - 0.68)	Trivial	0.8 ± 16.3	0.15 (-0.69 - 0.98)	Trivial
	$t_{F50\%}$ (ms)	1.0 ± 5.3	0.03 (-0.59 - 0.65)	Trivial	1.3 ± 6.0	-0.07 (-0.69 - 0.55)	Trivial	-0.7 ± 7.1	0.06 (-0.77 - 0.90)	Trivial
	$t_{F90\%}$ (ms)	1.9 ± 4.4	0.01 (-0.61 - 0.63)	Trivial	3.4 ± 5.3	-0.14 (-0.76 - 0.48)	Trivial	0.2 ± 5.3	0.01 (-0.82 - 0.85)	Trivial
	$t_{F50\text{-}90\%}$ (ms)	3.1 ± 6.9	-0.17 (-0.80 - 0.45)	Trivial	6.4 ± 6.4	-0.54 (-1.17 - 0.10)	Moderate	1.8 ± 3.1	-0.19 (-1.03 - 0.65)	Trivial
	t_{500N} (ms)	4.2 ± 7.5	-0.24 (-0.86 - 0.39)	Trivial	8.1 ± 9.1	-0.17 (-0.79 - 0.46)	Trivial	0.1 ± 8.7	-0.02 (-0.86 - 0.81)	Trivial
	F_{5ms} (N)	-4.0 ± 8.6	0.08 (-0.54 - 0.70)	Trivial	-9.7 ± 8.6	0.18 (-0.44 - 0.81)	Trivial	-2.4 ± 11.7	0.19 (-0.65 - 1.03)	Trivial

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Table 7.2 continued

Lead hook	Peak force (N)	-4.9 ± 7.3	0.33 (-0.30 - 0.95)	Small	-12.9 ± 8.2	0.80 (0.16 - 1.45)	Moderate	-2.0 ± 6.0	0.19 (-0.64 - 1.03)	Trivial
	Relative force (N·kg^{-1})	-4.9 ± 7.3	0.30 (-0.32 - 0.93)	Small	-12.9 ± 8.2	0.85 (0.21 - 1.50)	Moderate	-2.0 ± 6.0	0.20 (-0.64 - 1.04)	Trivial
	Impulse (N·s)	-2.7 ± 7.6	0.17 (-0.45 - 0.79)	Trivial	-5.5 ± 9.1	0.30 (-0.32 - 0.93)	Small	-1.3 ± 6.8	0.05 (-0.79 - 0.88)	Trivial
	$t_{F50\%}$ (ms)	1.6 ± 4.7	-0.13 (-0.75 - 0.49)	Trivial	4.5 ± 7.0	-0.26 (-0.88 - 0.36)	Small	3.0 ± 3.7	-0.21 (-1.05 - 0.63)	Trivial
	$t_{F90\%}$ (ms)	2.3 ± 4.2	-0.20 (-0.82 - 0.43)	Trivial	5.6 ± 6.9	-0.37 (-0.99 - 0.26)	Small	2.5 ± 2.9	-0.22 (-1.06 - 0.62)	Trivial
	$t_{F50\text{-}90\%}$ (ms)	3.5 ± 4.4	-0.29 (-0.91 - 0.33)	Small	7.6 ± 8.1	-0.59 (-1.22 - 0.05)	Moderate	3.4 ± 5.9	-0.24 (-1.08 - 0.60)	Trivial
	t_{500N} (ms)	4.6 ± 7.6	-0.31 (-0.93 - 0.32)	Small	14.1 ± 11.8	-0.72 (-1.36 - -0.08)	Moderate	4.3 ± 5.9	-0.29 (-1.13 - 0.55)	Small
	F_{5ms} (N)	-6.0 ± 11.3	0.36 (-0.27 - 0.98)	Small	-17.5 ± 12.6	0.71 (0.07 - 1.35)	Moderate	-5.5 ± 7.5	0.30 (-0.54 - 1.14)	Small
Rear hook	Peak force (N)	-2.9 ± 8.5	0.14 (-0.49 - 0.77)	Trivial	-9.0 ± 6.7	0.14 (-0.49 - 0.77)	Trivial	-1.1 ± 13.4	0.20 (-0.64 - 1.04)	Trivial
	Relative force (N·kg^{-1})	-2.9 ± 8.5	0.31 (-0.32 - 0.94)	Small	-9.0 ± 6.7	0.42 (-0.21 - 1.05)	Small	-1.1 ± 13.5	0.19 (-0.64 - 1.03)	Trivial
	Impulse (N·s)	-0.6 ± 8.7	0.15 (-0.48 - 0.78)	Trivial	-2.6 ± 10.6	0.17 (-0.45 - 0.79)	Trivial	0.8 ± 16.3	0.07 (-0.77 - 0.90)	Trivial
	$t_{F50\%}$ (ms)	1.0 ± 5.3	-0.16 (-0.78 - 0.47)	Trivial	1.3 ± 6.0	-0.20 (-0.82 - 0.43)	Trivial	-0.7 ± 7.1	-0.29 (-1.13 - 0.55)	Small
	$t_{F90\%}$ (ms)	1.9 ± 4.4	-0.21 (-0.84 - 0.42)	Trivial	3.4 ± 5.3	-0.31 (-0.93 - 0.32)	Small	0.2 ± 5.3	-0.50 (-1.35 - 0.35)	Small
	$t_{F50\text{-}90\%}$ (ms)	3.2 ± 5.7	-0.21 (-0.83 - 0.41)	Trivial	5.5 ± 8.6	-0.36 (-0.98 - 0.27)	Small	9.8 ± 10.5	-0.75 (-1.61 - 0.12)	Moderate
	t_{500N} (ms)	4.2 ± 7.5	-0.26 (-0.89 - 0.37)	Small	8.1 ± 9.1	-0.35 (-0.97 - 0.28)	Small	0.1 ± 8.7	-0.28 (-1.12 - 0.57)	Small
	F_{5ms} (N)	-4.0 ± 8.6	0.25 (-0.38 - 0.89)	Small	-9.7 ± 8.6	0.43 (-0.19 - 1.06)	Small	-2.4 ± 11.7	0.27 (-0.57 - 1.11)	Small
Physio-logical response	Average HR (bpm)	-0.8 ± 4.2	0.07 (-0.60 - 0.73)	Trivial	7.1 ± 6.0	-0.83 (-1.49 - -0.17)	Moderate	6.4 ± 3.7	-1.03 (-2.00 - -0.06)	Large
	Peak HR (bpm)	-1.5 ± 4.6	0.16 (-0.50 - 0.83)	Trivial	4.2 ± 5.0	-0.52 (-1.17 - 0.14)	Moderate	5.0 ± 3.7	-0.91 (-1.87 - 0.04)	Moderate
	RPE (a.u.)	-4.1 ± 9.2	0.48 (-0.15 - 1.11)	Small	23.2 ± 16.1	-1.58 (-2.28 - -0.87)	Large	27.0 ± 20.9	-1.49 (-2.43 - -0.55)	Large
	[La$^-$] (mmol·L^{-1})	-10.1 ± 40.3	0.50 (-0.13 - 1.13)	Moderate	262.6 ± 159.0	-3.31 (-4.26 - -2.35)	Large	223.2 ± 92.9	-2.25 (-3.32 - -1.18)	Large

Differences between pre- and post-intervention 3MPT under a control (CON), rowing (ROW) and boxing (BOX) conditions. Values are percentage change (%Δ) expressed as mean ± SD; effect sizes are Cohen's *d* (95% confidence interval); effect size are classified according to Rhea [83].

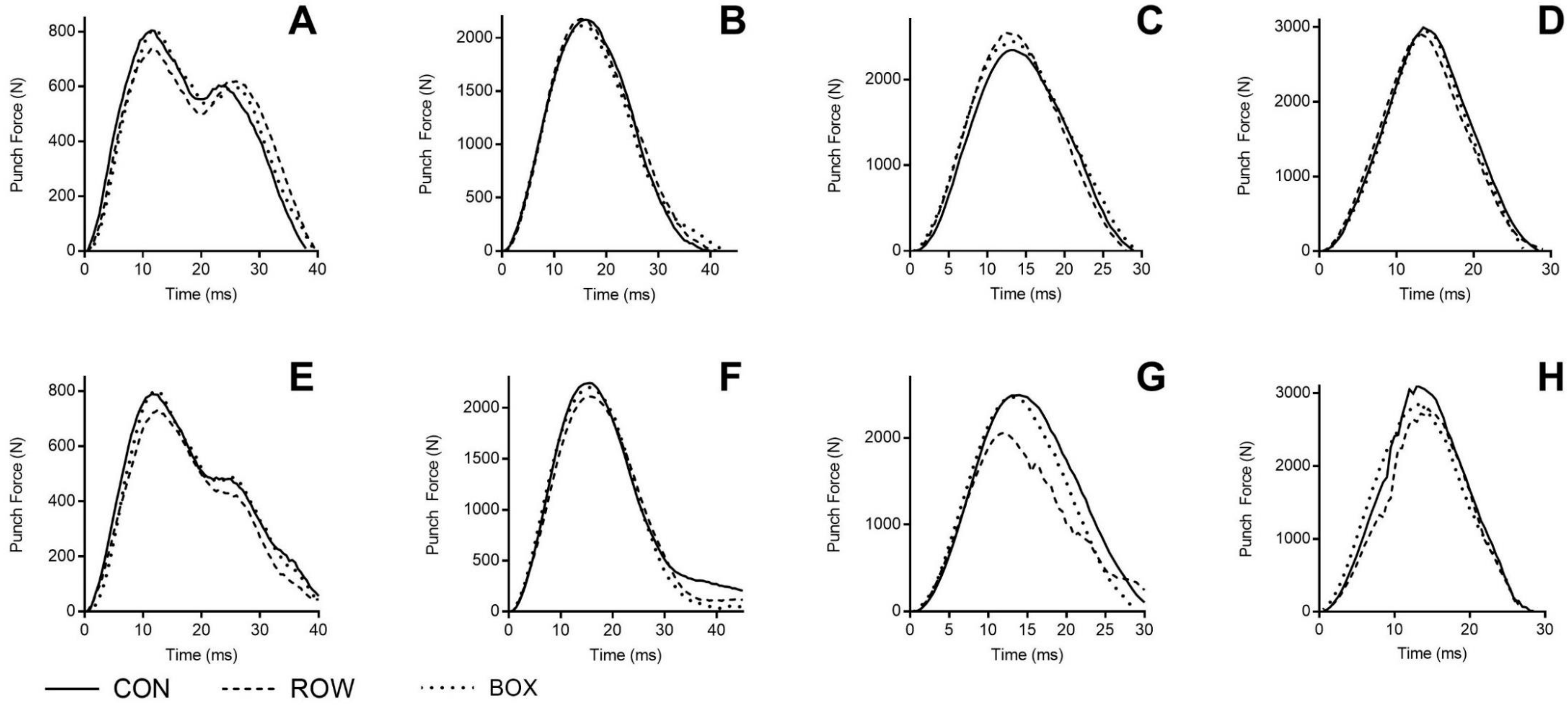

Figure 7.1. Example force traces for punches delivered in the 3-min punch test (3MPT) under control (CON), rowing (ROW) and boxing (BOX) conditions; panels A - D: pre-intervention data for jab (A); cross (B); lead-hand hook (C); rear-hand hook (D); panels E - H: post-intervention data for jab (E); cross (F); lead-hand hook (G); rear-hand hook (H).

7.5 Discussion

Punch force is positively related to boxing bout success in competitive boxing [61] and previous researchers have stated that punch force is expected to be significantly and negatively impacted by muscular (and perceptual) fatigue [54]. The present research examined the effect of both boxing-specific (i.e. competitive bouts) and non-specific (i.e. rowing exercise) muscular activity on the ability to produce punch force in highly-trained boxers. The main results of the present research were that lead-hand punches were the most susceptible to fatigue induced in the lower body and trunk by high-intensity rowing, while a competitive boxing bout had no detectable effects on participants' abilities to produce punch force (Figure 7.1). This is despite the physiological responses to the rowing and competitive sparring bouts being similar. While the use of simulated competition boxing bouts was necessary to obtain HR and [La^-] measurements, using unofficial bouts represents a limitation of the current study. Nonetheless, numerous steps were taken to create a representative competition environment, including having official referees and judges officiate the bouts and offering the winner of the bout an incentive. Thus, while unofficial, the results of this study are relatively comparable to other competitive boxing bouts.

The reduction in punch force observed after the intense rowing bout, but absence of change in punch force after competitive boxing, is most likely attributable to the different physical demands and biomechanics of the prescribed tasks. The fatiguing rowing exercise was prescribed because the hip and knee extensor muscles are used to generate torque about the hip and knee joints and thus fatigue in the lower body and trunk should result [14, 121]. Given that these muscle groups are also important for the production of punch force [4, 64], it is possible that the resultant fatigue affected the biomechanics and muscle activation patterns during the punching action. Conversely, the movement patterns of the lower body (locomotive action i.e. footwork) during a competitive boxing bout are likened to skipping or bouncing movements [116]. While the muscle activation patterns involved in the locomotive movements during boxing have not been described, the muscles of the calf are likely to be the main contributors in this activity. During a bouncing movement, the calf muscles and Achilles tendon operate in a stretch shortening cycle manner to generate force, however previous research has shown these muscles are largely resistant to fatigue [122, 123], as might be otherwise expected in repetitive bouncing activities such as standard boxing foot movements. Speculatively, the potential fatigue induced by boxing footwork should be minimal and manifest mainly in the calf muscles, in contrast to the substantial fatigue of the trunk and lower body induced by rowing, and is speculated to be less functionally important in the generation of punch force. Therefore, it is possible that comparable heart rate responses and blood lactate concentrations were evoked in rowing and sparring exercise, but the functional deficit was minimal after boxing.

Discrepancies in the responses to rowing and sparring exercise could also be related to pacing constraints imposed during the exercise bouts. During the rowing bout, participants were tasked with meeting 90% of the distance obtained during their 1-min all-out maximal trial for nine repeated efforts. The repeated and high-intensity nature of these bouts means that the ability for participants to regulate their workload (i.e. pace) was limited, and a near-maximum effort was required from both right and left upper and lower body musculature to complete the rowing task [14, 121, 124]. Conversely, during the sparring bout, the participants were free to tactically regulate their workload according to their perception of what was required to win. So in addition to having boxing-specific muscular endurance adaptations, the aim of beating their opponent regardless of the level of effort required may have offered boxers the chance to regulate their effort by changing tactics if fatigue was perceived. This might include distributing loads between lead and rear hands according to the capacity and fatigability of each arm, allowing the maintenance of high punch forces during and after the boxing condition by selectively (and potentially unevenly) distributing the workload between their lead and rear hands.

The notion of pacing throughout competitive boxing bouts and boxing-specific activity is not a novel concept. Previous investigations (including Study 1) have also inferred that pacing may be, in part, responsible for observed changes in behaviour and tactics in boxers, such as a reduction in bouncing during locomotion, increased time spent in clinches, and dropping the guard during the bout [3, 22, 24, 93]. Increased performance variability has been implicated as a pacing strategy in sports such as cycling, as a way of maintaining velocity [90]. Also, several authors have reported alterations in muscle recruitment patterns, visible changes in technique, and altered tactics or behaviour as a result of fatigue or pacing in an effort to avoid fatigue, in elite athletes from numerous other sports [13-15]. Hence, it is possible that the performance variability observed in the present study (i.e. seen in ICC and CV results) reflects a pacing strategy similar to other boxing-specific (Study 1 and Study 4 [93]) and non-specific settings [13-15]. This previous research provides evidence to suggest that boxers in the present study may have paced their effort throughout the BOX intervention bout in order to avoid fatigue and maintain punch force, hence, no significant reduction in punch force was observed.

In summary, the results of the present study showed that the ability of highly-trained boxers to produce impact force in punches from the lead hand was significantly impaired after high-intensity rowing exercise that induced fatigue in the lower body and trunk [112-114], however punch force seemed to remain unchanged for all punch types after a bout of competitive boxing. The fatigue caused in the rowing task probably affected the leg and trunk muscles [112-114], which are important for punching [65, 67], whereas sparring was likely to involve muscle exertion from the calves and upper body [116], which are less likely to adversely affect punch force. The findings indicate that highly-trained boxers are able to maintain their punch force levels throughout and after a competitive bout, which may be a result of boxer's being specifically trained for the task or from the effective use of pacing strategies throughout the bout. It is possible that the participants utilised pacing strategies to minimise any fatiguing effect the bout induced, and were able to apply consistent punch forces throughout the bout. As such, it is important to consider the effects of pacing (i.e. altering behaviour to conserve energy) on judges' perception of dominance, and ensure that boxers are adequately conditioned to be able to withstand the possible fatiguing effects of a competitive boxing bout so that punch force is not affected and pacing strategies that involve noticeable behaviour change are not necessary. Future research might involve the comparison of winners and losers and use notational behavioural analysis together with punch force measurements to better quantify the influence of pacing behaviours and punch force production together on the outcome of competitive boxing bouts.

CHAPTER 8.

General discussion

8.1 General discussion and conclusions

The research contained in this thesis aimed to identify the factors associated with success in amateur boxing bouts contested under the TPMS, as well as the physical factors related to producing high punch impact forces and the effect of fatigue in both cases. In doing so, a boxing-specific punch performance test was developed and then implemented to assess punch impact force and the effect of both boxing-specific and non-specific fatiguing exercise on it. The results of this research enable a more thorough and detailed understanding of the current, subjective competition judging criteria and the physical requirements and demands involved in high-level amateur boxing. Specifically, the results of the research contained in this thesis provide evidence that the likelihood of victory under the TPMS may be most associated with the level of punch accuracy achieved by a boxer. In addition, a boxer's movement style, which may be affected by fatigue, also had a small but potentially important effect on the outcome of a bout. Moreover, competitive boxing bouts were associated with notable changes in boxing-specific movements from rounds 1 to 3, including intermittently dropping the guard, increased clinching, and a change towards a 'translational' movement style (i.e. becoming flat-footed and bouncing less). As such, these might present subjective cues to a judge regarding the physical state of a boxer and thus influence perception of dominance. The results of the research in this thesis also indicated that lower-body force production was related to the level of punch impact force produced in highly-trained boxers. Furthermore, lower-body fatiguing exercise (similar to the type that might be used in training) had a negative effect on punch force production, which is crucial to inflict damage to, or display dominance over, an opponent and therefore achieve victory. However, no evidence of competitive boxing bouts negatively affecting punch force production in highly-trained boxers was found, even though several behavioural alterations that may influence judge perception of dominance were observed.

Under the TPMS, amateur boxers are challenged to convince a panel of judges of their fight superiority and dominance over their opponent. The first descriptive study in this thesis (Chapter 3) assessed technical factors similar to those reported by Davis et al. [3], as well as behavioural and perceptual factors that were considered to potentially indicate the presence of fatigue or influence the outcome of a competitive bout. Some results were consistent with previous reports, showing that punch accuracy (i.e. landing a high percentage of punches whilst also minimising the percentage of air swing punches) was the most important factor for success. In Study 1, the total number of punches thrown was similar to that reported by Davis et al. [3], although the number landed and the number of defensive actions were both found to be higher in the present research, resulting in approximately 110 offensive and defensive actions per round. These differences may be attributed to the different level of competition used during data collection (world championship tournament in that study versus national championship tournament in the current research) or differences in the notational analysis techniques. By providing clear definitions of the variables and subsequently reporting high inter- and intra-tester reliabilities, the methods used in Study 1 provide a template that might be used in the future to increase the comparability of results reported by different performance analysts. Common variables reported by Davis et al. [3] and in the current research, such as referee stop times and clinch times, were similar, indicating that the bouts were judged comparably. The novel behavioural variables obtained in Study 1 revealed that boxers dropped their guard more and adopted a more translational movement style (i.e. become flat-footed) as the bout progressed. An interesting finding of the present research was that punch accuracy (percentage of punches landed of the total number thrown), when used in combination with a movement index that describes the ratio of how much time a boxer moved with a bouncing versus flat-footed movement pattern (using logistic regression), was found to be the best predictor of bout outcome. The model predicted 85% of bout results correctly, indicating that these two factors were substantially influential. Davis et al. [3] suggested that the perception of judges may be influenced by factors more complex than the accuracy of the punch exchanges between boxers when using the TPMS. The data from Study 1 support this suggestion and provide evidence that behavioural factors such as movement style are influential in the outcome of a competitive bout judged under the TPMS. In addition, this study provides evidence suggesting that behavioural changes are associated with the perception of fatigue in competitive boxing bouts.

The second study within this thesis (Chapter 4) reported on the design and both the reliability and accuracy of a boxing-specific punching test, the 3-min punch test (3MPT). Importantly, the mechanical assessment of the punch integrator system, on which the 3MPT was performed, revealed very good reliability and accuracy (< 0.1% error), allowing data from 3MPT trials to be interpreted with confidence. After adequate familiarisation, boxers could reliably complete the 3MPT, with overall scores (i.e. all punches analysed together) showing CVs of 2.3 - 5.1%, indicating the test had the sensitivity to detect moderate-to-large changes in punch force production (i.e. TE less than $SWC_{0.6}$). Reliability of the 3MPT improved from test day 1 to test day 2, indicating that a learning effect was present. The punch forces observed in this research were lower than punch forces previously reported in elite- and intermediate-level boxers, and is likely to reflect differences in population demographics. While the participants who volunteered for the present research were highly-trained (categorised as elite or junior elite) boxers they were younger on average than participants in many previous studies [5, 7, 56-58, 66]. In addition, the majority of previous studies reported forces obtained during single maximal punches, while in the 3MPT the punch forces were measured continuously for one 3-min round. The 3MPT was designed to closely replicate the work rates reported in Study 1, and elicited slightly lower HR responses to those previously reported in competitive bouts, but similar to those reported in other controlled testing protocols [11, 23, 41, 48, 49]. The [La^-] values reported after the 3MPT were lower than after a 3 × 3-min competition bout but comparable to simulation bouts previously reported [11, 23]. Average and peak HRs and [La^-] responses observed in Study 2 were reproduced in the 3MPT performed in Studies 4 and 5, suggesting that repeatable physiological responses are evoked by the test, even in different cohorts of boxers performing the tests months apart.

The development and assessment processes for the 3MPT, and punch integrator system, aimed to address many of the limitations presented in previous literature. By assessing and reporting the reliability and accuracy of the 3MPT, the present research has overcome a major limitation of other studies that did not provide sufficient methodological detail nor report the measurement reliability or accuracy of the tools used to collect punch force data. In Studies 2 - 5, the punch integrator was set to continuously sample at 2000 Hz for the duration of the test, which was much greater than the sampling rate used by many other researchers [5, 7, 12, 55-58]. Further to this, the 3MPT included the assessment of four different punch types (jab, cross, lead- and rear-hand hook) with calculation of a comprehensive and novel list of variables, including punch force, relative punch force, punch impulse, and multiple RFD variables. The 3MPT allows for a comprehensive analysis of these four punch types and provides a reliable tool to assess punch force characteristics. It thus allows for the evaluation of the effectiveness of training interventions, performance preparations strategies, and other practices relevant to punch force production.

The third and fourth studies (Chapters 5 and 6) document relationships between lower-body strength and power characteristics and the ability to produce punch impact force. Previous research investigating the relationship between muscular strength and power characteristics and punch force production reported that many upper- and lower-body strength and power variables were correlated with peak punch force [12]. While physical strength and power are undoubtedly important factors for producing punch force [102], the heterogeneous group of male and female boxers with large between-subject variation studied in previous research decreased the likelihood of identifying discriminating physical factors relating to punch force (i.e. correlation inflation was present). In Study 3 of the present research, relationships between muscular strength and power measurements and punch force production variables were examined in a relatively homogeneous sample of highly-trained male boxers. The results of the study add to previous findings by showing that lower-limb strength (and power to a lesser degree) characteristics were correlated with punch force whilst upper-body strength, power and RFD, as well as lower-body RFD were not correlated with punch force production variables.

The hypothesis that lower-limb strength may influence punch force production was more explicitly tested in Study 4. A high-intensity rowing protocol was used to induce fatigue in the lower-limb and trunk muscles, and the effect of this fatigue on punch force was assessed using the 3MPT. The results revealed significant reductions in peak punch force for the four punch types assessed as well as significant reductions in punch RFD in the cross and hook punches. These findings reveal the negative effect of muscular fatigue on punch force production and provide evidence that lower-body and trunk force contributions might be of substantial importance to punch force production. Findings from Study 1 had revealed that perception of fatigue increased significantly in each round of a competitive bout, and even though the physiological responses to the rowing exercise in Study 4 (i.e. HR, [La$^-$] and RPE of 183 ± 12 bpm, 11.6 ± 1.8 mmol·L^{-1} and 19 ± 2 a.u. respectively) were comparable to the responses reported during boxing in previous literature, it remained to be determined whether this fatigue was comparable to that experienced in a competitive boxing bout, such as the bouts described in Study 1.

The final study of this thesis (Study 5; Chapter 7) therefore examined the effects of rowing- versus boxing-induced muscular fatigue on punch force production in highly-trained boxers, to determine whether boxing activity elicited a similar functional deficit to the rowing-induced deficit observed in Study 4. Results of Study 5 showed that, as in Study 4, punch impact force was significantly impaired by fatiguing rowing exercise, however there were no significant reductions in punch force production after the competitive boxing bout. This result is probably best explained by the muscle groups being most affected by boxing versus rowing activities being different, and this resulted in different test responses in the post-exercise 3MPT. Rowing exercise largely affects the arm flexor and hip and knee extensor muscles [14, 112, 115, 121] whilst the bouncing and translational movement patterns adopted during boxing are probably largely reliant on the calf muscles, which do not fatigue as rapidly as the large hip and knee extensor muscles [4, 19, 64]. Thus, the larger lower-limb muscles that would be activated to initiate the forward momentum during a punch should still be able to produce sufficient force for high-force punching. Further to this, some level of upper-limb extensor muscle fatigue might be expected after boxing exercise, since these are key punching muscles (i.e. anterior deltoid, triceps brachii and pectoral muscles [105]), however this fatigue was not sufficient to detectably influence punch force production. Several possibilities that might be explicitly examined in future studies are that punch force was more impacted by rowing exercise than boxing because: 1) boxers were familiar with the boxing task and were able to resist fatigue during a competitive boxing bout, and 2) boxers were able to pace their effort during the bout, or manipulate their movement patterns as they fatigued in order to preserve punch force capacity despite the accumulated physiological fatigue (quantified by HR and [La^-] responses).

The results of Study 5 lead to an interesting hypothesis regarding fatigue during boxing competition that is worthy of examination. The results of Study 1 indicated that boxers' perceptions of fatigue and effort increased over the duration of a bout. In addition, behaviour changes such as guard dropping, clinching and adopting a translational movement style were observed as the bout progressed. The conclusion was reached that boxers were able to mitigate some level of fatigue by changing their behaviour and, potentially, conserving energy. The results of Study 5 indicate that there was no measurable decrease in the boxers' capacities to produce punch force after a competitive bout. Speculatively, boxers were able to maintain punch force in the final stages and after a competitive bout despite perceiving increased levels of fatigue and effort required by manipulating certain behavioural and tactical actions to conserve energy, as seen in Study 1. However, given that movement style parameters were found to influence the outcome of a competitive bout in Study 1, behaviour modification to maintain punch force capacity could have had a negative impact on the judges' perceptions of dominance (i.e. showing signs of fatigue might reduce the likelihood of winning). The results of Studies 1 and 5 collectively suggest that boxers might prioritise forceful punching over disguising behaviours that might indicate fatigue or the use of pacing strategies. Given that, at its core, boxing bouts involve hand-to-hand combat between skilled and motivated combatants and that punching the opponent with significant force has many benefits (i.e. gaining success by knockout or negatively affecting the opponents fighting capacity), it is not surprising that boxers aim to deliver maximum punch force throughout the entire bout. However, this may still be problematic in that cues may be given to judges that increase the risk of losing the bout. In addition, an opponent may also identify cues that are indicative of fatigue and manipulate their own behaviour to gain a competitive advantage. An important practical application of this information is that boxers should be adequately conditioned so that they can maintain punch force without having to change behaviour or pace throughout a bout, or they need to develop strategies to disguise fatigue and pacing strategies during competitive bouts. While studies 1 and 5 collectively provided interesting hypotheses, the comparison of data sets in two separate studies is limited and further research involving the analysis of both behavioural and punch force data together is required.

In summary, the research contained in this doctoral thesis indicates that judge perception of dominance during competitive boxing bouts adjudicated by the TPMS is influenced by both behavioural and technical elements of performance. In addition, success under the TPMS primarily requires high levels of punch accuracy (so that hit rates are increased and air punches are reduced) and the display of a bounce-like movement style. Lower- but not upper-body strength was found to be significantly and positively related to peak punch force production, while RFD in the upper and lower body was not. Consistent with this, fatigue of the lower body and trunk muscles significantly reduced punch force production. Nonetheless, boxers do not appear to experience significant reductions in punch force production after a competitive boxing bout, despite previous and present research suggesting that competitive boxing induces substantial muscular fatigue. It is hypothesised that boxers may manipulate their behaviour in the boxing ring to conserve energy so that punch impact force remains constant throughout the bout, although this might still have a negative influence on judge perceptions of superiority and dominance and thus on bout outcome. Further research is needed to provide supporting evidence for this hypothesis.

8.2 Directions for future research

Findings from the research presented in this thesis indicate that fatigue during boxing bouts may trigger changes in behaviour or the tactical approaches taken by amateur boxers during competition. In addition, fatigue in the important lower-body and trunk muscles directly reduces punch impact force, although punch force appears to be maintained when intense boxing exercise (sufficient to induce a significant physiological impact) is performed. Thus, mitigation of such fatigue through the use of pacing strategies, ergogenic aids, appropriate training practices, etc., might minimise any potential loss of punch force during competitive boxing bouts or during periods of fatiguing boxing training. It is also possible that improvements in lower-body and trunk muscle strength might help to improve punch force production. However, these possibilities are yet to be explicitly examined. Importantly, research evidence is not available to provide insight into how best to increase muscular strength without the simultaneous acquisition of muscle mass, which might be problematic for boxers aiming to compete within their current specific weight category. Finally, future research is required to identify additional behavioural or technical elements of boxing performance that might influence a judge's perception of superiority and dominance. Such information may underpin tactical approaches for amateur boxers contesting competition bouts. Such research might include the analysis of a wider range of behavioural variables during competitions of varying standards, and interviewing amateur boxing judges directly. In-depth understanding of fatigue and boxing will be facilitated as more advanced wearable technology provides scientists with kinetic and kinematic feedback during actual fights.

CHAPTER 9.

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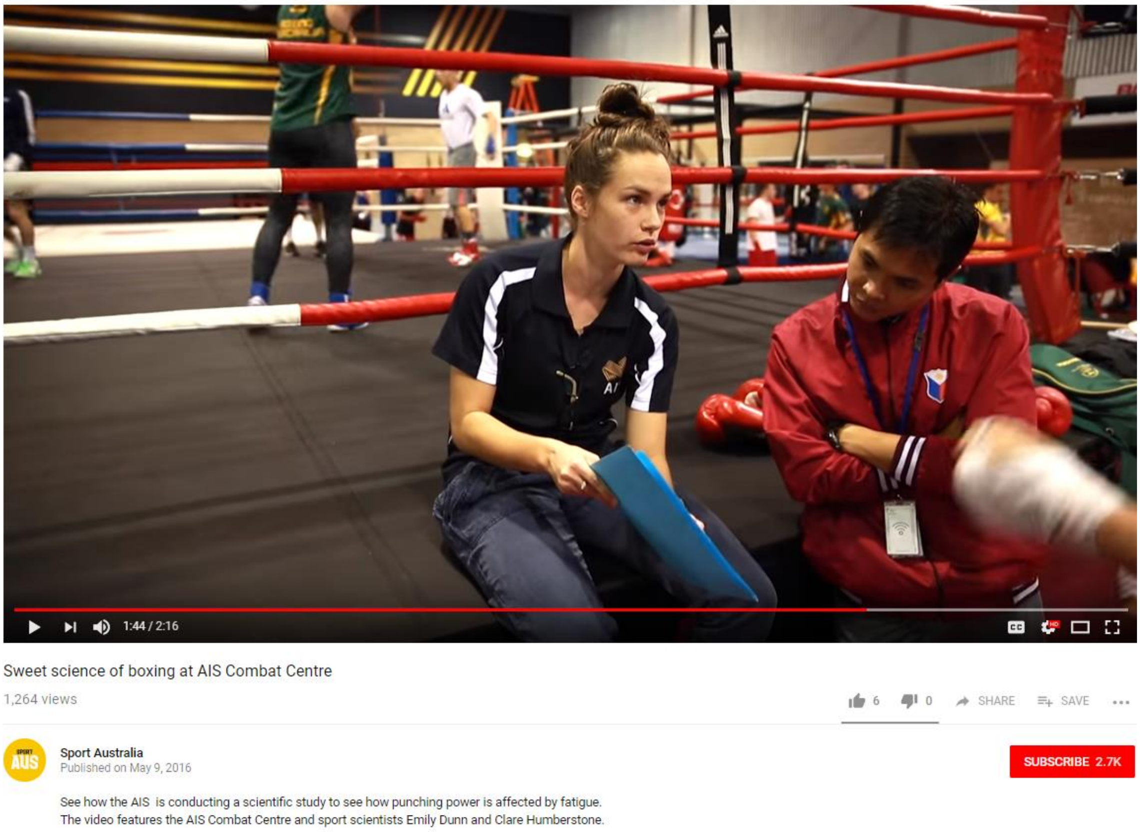
CHAPTER 10.

Appendices

List of appendices

Appendix A - Photos

(A)

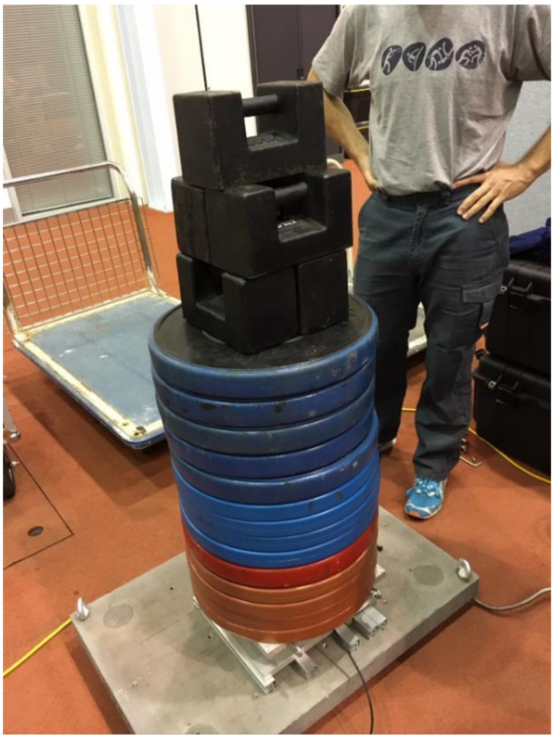


(B)

Screenshots (A - B) of AIS media video focusing on 3MPT testing at an international boxing camp. Full video, including 3MPT footage:

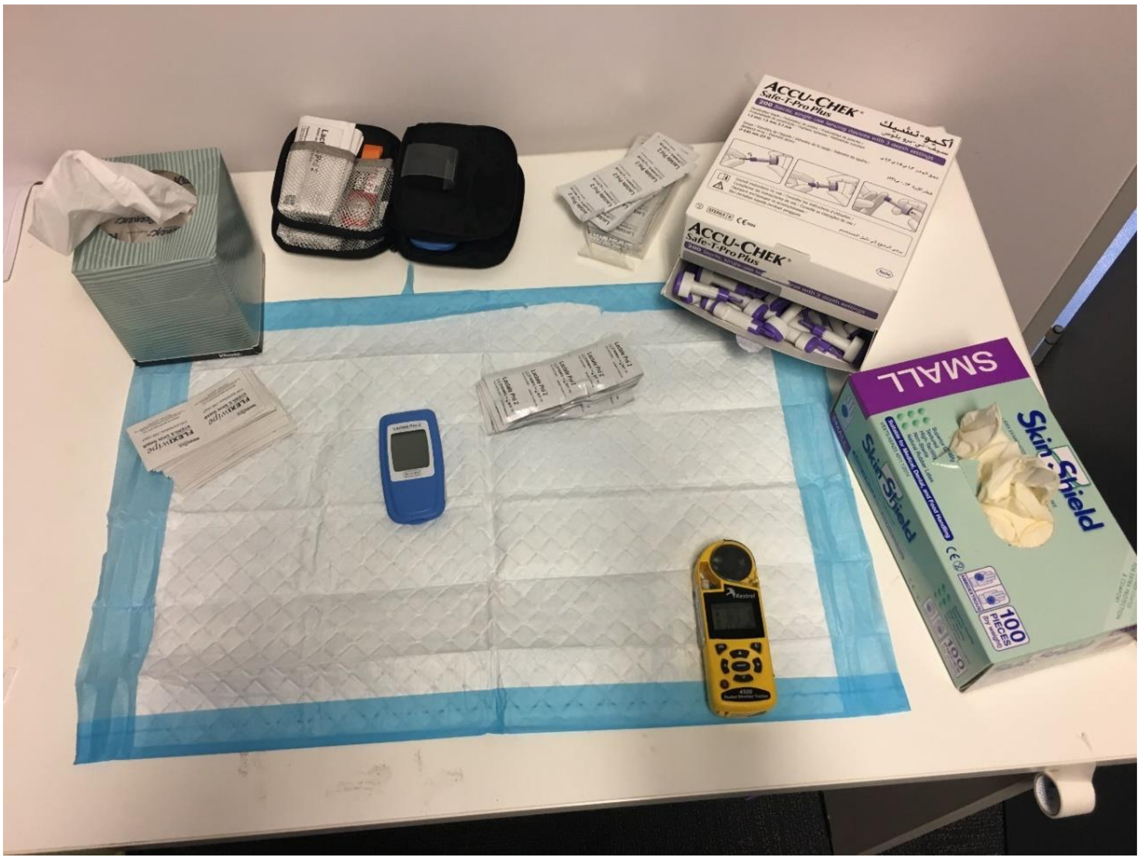
https://www.youtube.com/watch?v=r9iZ_PMv4wM

(C) 

(D) 

(E) 

(F)



(G)

Photos (C - G) from data collections (Studies 2 - 5)

Appendix B - Ethics approval for PhD: ECU Human Research Ethics Committee

Edith Cowan University

Confirmation of candidature for Emily DUNN PhD (HES)

Message By Email (Russell Tassicker) (30/04/2015 02.05 PM)
30 April 2015

Miss Emily Dunn
155 Lampard Circuit
BRUCE NSW 2617

Dear Miss Dunn,

I am pleased to write on behalf of the Research Students and Scholarships Committee who have approved your PhD research proposal: **Manifestations of fatigue in boxing: investigating the role of soft-tissue vibration.**

I also wish to confirm that your proposal complies with the provisions contained in the University's policy for the conduct of ethical research, and your application for ethics has been approved. Your ethics approval number is **12233** and the period of approval **26 March 2015** to **31 December 2017**.

Approval is given for your supervisory team to consist of:

Principal Supervisor: A/Prof Anthony Blazevich – ECU
Associate Supervisor: Mrs Fiona Iredale - ECU
Associate Supervisor: Dr David Martin – AIS
Associate Supervisor: Dr Clare Humberstone – AIS

The examination requirements on completion are laid down in *Part VI of The University (Admissions, Enrolment and Academic progress) Rules for Courses Requiring the Submission of Theses* available at: http://ww.ecu.edu.au/GPPS/legal_legis/uni_rules.html

Additional information and documentation relating to the examination process can be found at the Graduate Research School website: http://research.ecu.edu.au/grs/

Please note: the Research Students and Scholarship Committee has resolved to restrict doctoral theses to a maximum of 100,000 words with a provision that under special circumstances a candidate may seek approval from the Faculty Research and Higher Degrees Committee for an extension to the word length. (RSSC 99/24).

I would like to take this opportunity to offer you our best wishes for your research and the development of your thesis.

Yours sincerely

Russell Tassicker
Senior Student Progress Officer
Research Assessments - SSC
Phone: 08 6304 8770
Email: researchassessments@ecu.edu.au

Appendix C - Ethics extension for PhD: ECU Human Research Ethics Committee

Emily Dunn

From:	Research Ethics <research.ethics@ecu.edu.au>
Sent:	Tuesday, 5 December 2017 11:24 AM
To:	Emily Dunn
Cc:	Tony BLAZEVICH; Fiona IREDALE
Subject:	12233 DUNN annual ethics report receipt and extension approval

Hi Emily

Project Number: 12233 DUNN
Project Name: Manifestations of Fatigue in Boxing: Investigating the Role of Soft-Tissue Vibration

Thank you for your ethics report.

Your request for an extension of ethics approval for this project has been granted until 31 December 2018.

Kind regards,

Sue

Sue McDonald, Research Ethics Support Officer, 34.341, Office of Research & Innovation, Edith Cowan University, 270 Joondalup Drive, Joondalup, WA 6027
Email: susan.mcdonald@ecu.edu.au Tel: +61 08 6304 2784 | Fax: +61 08 6304 5044 | CRICOS IPC 00279B

Appendix D - Document of Informed Consent Study 1

Information for Participating Athletes

Project: Physiological and Perceptual Manifestations of Fatigue in Elite Boxers

Background:
The purpose of this project is to explore the ways in which fatigue develops in athletes during boxing competition. In order to understand boxing-relevant fatigue, we must first understand the demands of competitions. Subsequently, it will be possible to better examine the effects of acute and chronic interventions proposed for competitive boxers.

Project Outline:
Participation in this project is completely voluntary and you may decline or withdraw consent at any point without prejudice or becoming disadvantaged in any way. This project requires you to complete a short survey after you complete one of your boxing matches relating to fatigue you may have felt during the match. Your match will also be filmed with an overhead depth camera. The procedures are described further in this letter.

The Research Team: This project involves researchers from the Australian Institute of Sport (AIS) and Edith Cowan University (ECU). This research project is being undertaken as part of the requirements of a PhD at Edith Cowan University.

Emily Dunn (PhD candidate), AIS: Emily.Dunn@ausport.gov.au
Dr David Martin (Supervisor), AIS: David.Martin@ausport.gov.au
Dr Clare Humberstone (Supervisor), AIS: Clare.Humberstone@ausport.gov.au
Dr Anthony Blazevich (Supervisor), ECU: a.blazevich@ecu.edu.au
Fiona Iredale (Supervisor), ECU: f.iredale@ecu.edu.au

Risks to Participants:
There is some risk of discomfort or harm that comes with participation in amateur boxing; however, your inclusion in this study does not place you at any additional risk than what you're exposed to during your participation in this tournament

Benefits:
Movement patterns observed during this tournament have never been analysed in relation to coach and athlete perception of fatigue. The information gathered will provide unique insight into the effects of fatigue on boxing performance. This information can assist coaches, athletes and trainers in refining their preparation for boxing tournaments in the future. This is of particular importance during the lead up to the Olympic Games in 2016.

Confidentiality:
All results obtained during this study will remain confidential. For the purpose of this study, names will not be reported with results at any time and will not be available to anyone other than the investigative team. Data from this study will however be used by the ASC for the purpose of performance analysis and training, and in a de-identified form (you will remain anonymous), for the purpose of research, education and publication. This research project is part of a doctoral thesis, and de-identified data will be published in academic journals and presented to academics at domestic and international conferences. The data collected in this project may be used in future publications in a de-identified form. Data will be stored on password-protected computers and hard disk. If you volunteer to participate, we will ask you to complete and sign an informed consent form.

Testing Protocols:

***Perceptual measures**:* After the completion of one of your (or your boxer's) matches, you will be asked to fill in a short survey to do with the how you (or the boxer) performed, and how fatigue was involved with this performance. This survey should not take more than 5 minutes to complete.

Competition Monitoring (Performance Assessment): While athletes contest routine competition sparring, variables can be measured according to the protocols described above (e.g. perceptual measures) to gather information about their performance and fatigue during competition. Performance in the ring will also be videoed to gather performance information (e.g. retrospective fight performance analysis).

Further Information:

For further explanation of the Physiological and Anthropometric assessment procedures, please contact the Physiology Laboratory Manager on (02) 6214 1895, the principal investigator, Emily Dunn on 04 78659301 or Emily.dunn@ausport.gov.au or the principal supervisor, Anthony Blazevich on (08) 6304 5472.

***Independent contact person*:** If you have any concerns or complaints about the research project and wish to talk to an independent person, you may contact:

Research Ethics Officer
Edith Cowan University
270 Joondalup Drive
JOONDALUP WA 6027
Phone: (08) 6304 2170
Email: research.ethics@ecu.edu.au

This project has been approved by the ECU Human Research Ethics Committee and the Australian Institute of Sport Ethics Committee.

Physiological and Perceptual Manifestations of Fatigue in Elite Boxers

Statement of Informed Consent

1. I _______________________________________ (print name) acknowledge and agree that:
   a. I have been provided with a copy of the document 'Information for Participating Athletes', which describes the nature and associated risks and discomforts of the physiological and anthropometric tests I will participate in (competition sparring, punch force/speed assessment and maximal punch performance profiling) as part of the assessment (research project: the manifestation of fatigue in boxing). I have read and understood the contents of that document;
   b. I have been given an opportunity to ask questions and have received a satisfactory explanation about the nature, safety procedures and associated risks and discomforts of each test.

2. I agree that I will:
   a. present myself for the assessment in a suitable condition, having abided by the requirements for diet and activity prescribed for me by Australian Sports Commission (ASC) laboratory staff; and
   b. advise the ASC staff conducting the assessment of any illness, injury or other physical, mental or medical condition I have that may increase the risk of undertaking the assessment; or if I feel that I cannot complete the assessment safely for any other reason.

3. I understand that my participation in the assessment is voluntary and that I may withdraw my consent freely and without prejudice (e.g. without limiting any future opportunities) at any time before or during the assessment.

4. I understand that the information obtained by the ASC during the assessment will be treated confidentially, respecting my rights of privacy. However, I consent to the information being used by the ASC for the purpose of performance analysis and training, and in a de-identified form, for the purpose of research, education and publication in the future.

5. I release the ASC and its employees from any liability in relation to any injury or illness that I may suffer while undertaking the assessment or subsequently occurring in connection with the assessment; and for any loss or damage to property in connection with the assessment, except to the extent that such liability arises as a direct result of the negligence of the ASC.

6. I will ask for a copy of this signed form if I wish to retain one for my records.

Signature of Athlete: ____ Date: _____/_____/_______

Parent/Guardian name (required if Athlete aged under 18): ___________________________________

Parent/Guardian signature: ______________________________________ Date: _____/_____/______

I, the undersigned was present when the test procedures were explained to the athlete in detail and to my best knowledge and belief they were understood.

Witness name: ____ Date: _____/_____/_______

Witness signature: ____ Date: _____/_____/_______

Appendix E - Document of Informed consent Study 2 - 4

Information for Participating Athletes

Project: Manifestation of Fatigue in Amateur Boxing

Background:
The purpose of this project is to explore the manifestation of fatigue in boxing. To do so we must establish meaningful and specific testing protocols to assess boxing specific performance. This project will develop and test protocols for the assessment of boxing specific performance.

Project Outline:
Participation in this project is completely voluntary and you may decline or withdraw consent at any point without prejudice or becoming disadvantaged in any way. This project requires you to visit the AIS Combat Centre on 4 occasions for approximately 1 hour. During the first session you will be familiarised with all testing protocols and equipment (described below). You will be asked to complete the data collection sessions in a rested state and make the same dietary and activity considerations as if you were to be competing in a tournament. During this project you will be asked to engage in a boxing specific protocol. You will be asked to punch an instrumented punching bag with as much speed to force as you can for a set duration. This will depend on your standard competition format (e.g. 3 by 3 minutes bout or 4 by 2 minutes). During this protocol you will have your heart rate and respiration rate monitored as well as blood lactate measured using the methods explained below. You will also have your maximal punch force and speed measured before and after the protocol on the same instrumented punching bag (also described below). You will be asked to complete this protocol during 3 sessions before and after 30 minutes of rest. You will also have anthropometric and general strength and power measures taken (described below). During the boxing specific protocol you will be asked to rate your level of motivation (Situational Motivation Scale; SIMS) and physical and mental effort using two scales, the rating of perceived exertion (RPE) scale and the task effort awareness (TEA) scale.

The Research Team: This project involves researchers from the Australian Institute of Sport (AIS) and Edith Cowan University (ECU). This research project is being undertaken as part of the requirements of a PhD at Edith Cowan University.

Emily Dunn (PhD candidate), AIS: Emily.Dunn@ausport.gov.au
Dr Anthony Blazevich (Supervisor), ECU: a.blazevich@ecu.edu.au
Dr Clare Humberstone (Supervisor), AIS: Clare.Humberstone@ausport.gov.au
Fiona Iredale (Supervisor), ECU: f.iredale@ecu.edu.au

Risks to Participants:
There is some risk of discomfort or harm that comes with participation in amateur boxing; however, your inclusion in this study does not place you at any greater risk than that which would be experienced during training or competition. A trained first aider will be present during all simulated boxing matches to minimise the risk of discomfort or harm. Taking capillary blood can pose a small risk of infection, which will be minimised further by the application of alcohol to the area before and after the sample is collected.

Benefits:
You will be given information about your performances in all competition and testing (relative to the average). This boxing specific information can be of value to your training as you strive for state and national representation. The data given to you will provide an excellent comparison between yourself, the top boxers in Australia and the top boxers in the world. This is of particular importance during the lead up to the Olympic Games in 2016 and beyond as boxers are physically preparing for elite level competition.

Confidentiality:
All results obtained during this study will remain confidential. For the purpose of this study, names will not be reported with results at any time and will not be available to anyone other than the investigative team. Data from this study will however be used by the ASC for the purpose of performance analysis and training, and in a de-identified form (you will remain anonymous), for the purpose of research, education and publication. This research project is

part of a doctoral thesis, and de-identified data will be published in academic journals and presented to academics at domestic and international conferences. The data collected in this project may be used in future publications in a de-identified form. Data will be stored on password-protected computers and hard disk. If you volunteer to participate, we will ask you to complete and sign an informed consent form.

Testing Protocols:
Capillary Blood Test: Capillary blood samples (typically 5-75 microlitres or 1-15 small droplets) will be taken from either the earlobe or fingertip and are conventionally used to assess pH, lactate and bicarbonate values. A capillary blood sample is obtained by using a lancet device, which makes a small puncture into the skin. Gloves and lancets are single use only and are discarded after every sample. Samples are tested and discarded into biohazard bins immediately after collection to minimise the risk of infection. This procedure is not a diagnostic tool and will not provide information about your health status or blood disorders.

Anthropometry: Anthropometric assessment involves simple measurements of stature (height), body mass, skinfolds, girths, limb lengths and bone breadths. In addition skinfold thickness will be measured using handheld callipers across several sites depending on the level of assessment and needs of the athlete. The athlete undertaking the anthropometry measures is typically required to be dressed in underclothing. There is minimal physical discomfort associated with these measurements.

Submaximal Aerobic Power Test: Submaximal aerobic power tests assess cardiovascular fitness or aerobic power and involve exercising on an ergometer at low to moderate intensity that progressively increases throughout the test. For example, combat athletes punch or kick an instrumented surface for a prescribed period of time (usually according to competition demands, e.g. 3 x 3 minute rounds) while impact force and speed are monitored along with heart rate and respiration.

Anaerobic Power and Capacity Tests: Anaerobic power and capacity tests involve short duration maximal exercise efforts, and can be conducted in the laboratory or in the field using different modalities depending on the parameter to be measured and the protocol to be used. As with any exercise to maximal exertion there are potential associated risks, including temporary heavy breathing, muscular fatigue, episodes of light-headedness, fainting, abnormal blood pressure, nausea, and chest discomfort. Capacity tests for striking combat sports are completed on an instrumented punching bag (the 'punch integrator'). Athletes maximally strike (kick or punch) the surface for a fixed period of time (that mimics the demands of competition; e.g. 3 by 3 minutes rounds). This test requires a high level of skill and fitness and is only implemented in well-trained combat athletes.

Competition Monitoring (Performance Assessment): While athletes contest routine competition sparring, variables can be measured according to the protocols described above (e.g. heart rate and respiratory monitoring) to gather information about their performance during competition. Performance in the ring will also be videoed to gather performance information (e.g. retrospective fight performance analysis). Hand and foot speed will also assessed using small accelerometers inside the boxing gloves and laced into shoelaces. These competition sessions are run according to the International Boxing Association (AIBA) rules and guidelines.

Strength and Power Testing: Strength and power tests during this project include upper and lower body isometric strength, and upper and lower body power. During isometric contractions athletes push or pull on an immovable bar as hard as they can for 3-5 seconds. Dynamic power tests include jumping and throwing actions such as a court-movement jump, or squat jump. In all of these tests, force, rate of force development and power are measured or calculated using force plates and/or linear position transducers.

Further Information:
For further explanation of the Physiological and Anthropometric assessment procedures, please contact the Physiology Laboratory Manager on (02) 6214 1895, the principal investigator, Emily Dunn on 04 78659301 or Emily.dunn@ausport.gov.au or the principal supervisor, Anthony Blazevich on (08) 6304 5472.

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This project has been approved by the ECU Human Research Ethics Committee and the Australian Institute of Sport Ethics Committee.

Manifestations of Fatigue in Elite Boxers

Statement of Informed Consent

1. I _________________________________ (print name) acknowledge and agree that:
    a. I have been provided with a copy of the document 'Information for Participating Athletes', which describes the nature and associated risks and discomforts of the physiological and anthropometric tests I will participate in (competition sparring, punch force/speed assessment and maximal punch performance profiling) as part of the assessment (research project: the manifestation of fatigue in boxing). I have read and understood the contents of that document;
    b. I have been given an opportunity to ask questions and have received a satisfactory explanation about the nature, safety procedures and associated risks and discomforts of each test.

2. I agree that I will:
    a. present myself for the assessment in a suitable condition, having abided by the requirements for diet and activity prescribed for me by Australian Sports Commission (ASC) laboratory staff; and
    b. advise the ASC staff conducting the assessment of any illness, injury or other physical, mental or medical condition I have that may increase the risk of undertaking the assessment; or if I feel that I cannot complete the assessment safely for any other reason.

3. I understand that my participation in the assessment is voluntary and that I may withdraw my consent freely and without prejudice (e.g. without limiting future assessment opportunities) at any time before or during the assessment.

4. I understand that the information obtained by the ASC during the assessment will be treated confidentially, respecting my rights of privacy. However, I consent to the information being used by the ASC for the purpose of performance analysis and training, and in a de-identified form, for the purpose of research, education and publication.

5. I release the ASC and its employees from any liability in relation to any injury or illness that I may suffer while undertaking the assessment or subsequently occurring in connection with the assessment; and for any loss or damage to property in connection with the assessment, except to the extent that such liability arises as a direct result of the negligence of the ASC.

6. I will ask for a copy of this signed form if I wish to retain one for my records.

Signature of Athlete: ____________________________________ Date: _____/_____/_______

Parent/Guardian name (required if Athlete aged under 18): ______________________________

Parent/Guardian signature: ________________________________ Date: _____/_____/______

I, the undersigned was present when the test procedures were explained to the athlete in detail and to my best knowledge and belief they were understood.

Witness name: ____ Date: _____/_____/_______

Witness signature: _____________________________________ Date: _____/_____/_______

Witness signature: _____________________________________ Date: _____/_____/_______

Appendix F - Perceptual Questionnaire - Study 1

Athlete Survey

Name: Date:

What percentage of your maximal effort did you put into your **whole bout**?
0% ⊢——⊣ 100%

What percentage of your maximal effort did you put into **round 1**?
0% ⊢——⊣ 100%

What percentage of your maximal effort did you put into **round 2**?
0% ⊢——⊣ 100%

What percentage of your maximal effort did you put into **round 3**?
0% ⊢——⊣ 100%

How much did fatigue affect your performance during the **whole bout**? (Tick one)

Not at all	a little bit	somewhat	quite a bit	very much
☐	☐	☐	☐	☐

I don’t know
☐

Do you believe fatigue affected your performance during **round 1**? (Tick one)

Not at all	a little bit	somewhat	quite a bit	very much
☐	☐	☐	☐	☐

I don’t know
☐

Do you believe fatigue affected your performance during **round 2**? (Tick one)

Not at all	a little bit	somewhat	quite a bit	very much
☐	☐	☐	☐	☐

I don’t know
☐

Do you believe fatigue affected your performance during **round 3**? (Tick one)

Not at all	a little bit	somewhat	quite a bit	very much
☐	☐	☐	☐	☐

I don’t know
☐

If you believe fatigue affected your performance, how so?

____

____

____

____

____

Appendix G - Copy of publication (Study 1; pg 1)

PLOS ONE

RESEARCH ARTICLE

Human behaviours associated with dominance in elite amateur boxing bouts: A comparison of winners and losers under the Ten Point Must System

Emily C. Dunn[1,2]*, Clare E. Humberstone[2], K. Fiona Iredale[1], David T. Martin[2], Anthony J. Blazevich[2]

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Abstract

Humans commonly ascertain physical dominance through non-lethal fighting by participating in combat sports. However, the behaviours that achieve fight dominance are not fully understood. Amateur boxing competition, which is judged using the subjective "Ten Point Must-System", provides insight into fight dominance behaviours. Notational analysis was performed on 26 elite male competitors in a national boxing championship. Behavioural (guard-drop time; movement style [stepping/bouncing time]; clinch-time; interaction-time) and technical (total punches; punches landed [%Hit]; air punches [%Air]; defence) measures were recorded. Participants reported effort required (0–100%) and perceived effect of fatigue on their own performance (5-point Likert scale) following bouts. Differences between winners and losers, and changes across the duration of the bout were examined. Winners punched more accurately than losers (greater %Hit [33% vs. 23%] and lower %Air [17% vs. 27%]) but total punches, defence and interaction-time were similar. From rounds 1–2, clinch-time and guard drops increased whilst bouncing decreased. Perceived effect of fatigue increased throughout the bout while perceived effort increased only from rounds 2–3. %Hit and movement index together in regression analysis correctly classified 85% of bout outcomes, indicating that judges (subjectively) chose winning (dominant) boxers according to punch accuracy and style, rather than assertiveness (more punches thrown). Boxers appear to use tactical strategies throughout the bout to pace their effort and minimise fatigue (increased guard drops, reduced bouncing), but these did not influence perceived dominance or bout outcome. These results show that judges use several performance indicators not including the total number of successful punches thrown to assess fight dominance and superiority between fighters. These results provide valuable information as to how experienced fight observers subjectively rate superiority and dominance during one-on-one human fighting.

Appendix H - Copy of publication (Study 2; pg 1)

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ORIGINAL ARTICLE

WILEY

A damaging punch: Assessment and application of a method to quantify punch performance

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Measurement of punch performance in a reliable, quantitative manner is relevant to combat sport, military, and concussion research. A punching protocol (3MPT) was developed, based on performance demands of amateur boxing, and evaluated on a custom-built punch integrator (PI). PI reliability and accuracy were assessed by calculating TE and CV for a range of known masses. A within-subject, repeated-measures design assessed the test-retest reliability of 3MPT. Fifteen male boxers (17.5 ± 0.5 years; 177.5 ± 9.5 cm; 73.0 ± 14.0 kg) were familiarized and then completed two 3MPT trials 90 minutes apart on 2 days (total of four tests). Peak punch force (N), relative punch force (N/kg), impulse (N·s), and rate of force development calculated to various time points were compared using a linear mixed model. Smallest worthwhile change (SWC) was also computed. PI data were reliable and accurate (CV <0.1%). TE and SWC comparisons revealed that 3MPT can detect moderate and large changes in performance; however, within-day reliability improved from day 1 (3.1%-13.8%) to 2 (2.3%-5.1%) indicating a possible learning effect. Likewise, differences between test one and two were greater on day 1 than 2. Numerous punch-related variables can be accurately and reliably measured using the 3MPT but repeat-trial familiarization is suggested to reduce between-test variability.

KEYWORDS

boxing, fighting, force production, punch, reliability

1 | INTRODUCTION

A single powerful punch can inflict devastating physical damage, ending a fist fight by knockout. Alternatively, effective and powerful punches thrown continually and consistently throughout a fight in both sanctioned (combat sport) and non-sanctioned bouts can exert dominance and attain success.[1] Measurement of the force characteristics of various punch techniques is relevant for combat sports, forensic investigations of assault, military combat, and concussion research.

Research completed at the Australian Institute of Sport Combat Centre, Canberra, Australia.

Characteristics of forceful punches have been examined in single blows[2,3] and during combination punches[4] in controlled laboratory conditions. Researchers examining punch force or technique (kinematics) have often used indirect methods of measurement, for example three dimensional motion capture[4,5] and water-filled punching bags fitted with pressure sensors.[6] However, Smith et al[7] measured punch forces directly using a tri-axial dynamometer containing a piezoelectric transducer and were able to detect small differences in punch forces of elite, intermediate, and novice boxers. While peak punch force is undoubtedly an important factor in a damaging punch, head acceleration is the most damaging factor causing concussion.[8] Therefore measuring both force and other properties of punch impact (ie, force,

